
V. Fedynsky
Meteors

V. FEDYNSKY

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by G. YANKOVSKY

DESIGNED BY G. DAUMAN

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INTRODUCTION

On a dark cloudless night one may often see a point flame up and flash through the constellations like a "fallen" star. This is a meteor, from the Greek words *meta*, beyond, and *aiora*, hovering in the air. Formerly, meteors were often called shooting stars or falling stars but now these terms are hardly ever encountered in scientific writings for the reason that there is nothing at all in common between real stars—distant suns—and meteors that flame through the earth's atmosphere.

Meteors flare up as a result of small solid cosmic particles, meteoroids, colliding with the earth at a high relative speed between 10 and 70 km./sec. These particles dash into the upper layers of the atmosphere, heat up, and end in a terminal flare as they disintegrate (Fig. 1). The faster the particle moves and the greater its mass, the brighter is the meteor. Ordinarily, meteors glow at heights of 120 to 80 kilometres above sea level, though large particles may penetrate to lower-lying levels of the atmosphere. Very bright meteors that surpass Venus in brightness are called fireballs or bolides (from the Greek *bolis*, missile). Fireballs penetrate the atmosphere down to 50-55 kilometres, entering the denser layers of air. Here they produce waves of compression and rarefaction and are therefore accompanied by sound phenomena that at times are very powerful.

The sudden appearance of a fireball, its brilliant light, thunder-like claps that attend the flight, and, finally, the

huge smoke-like clouds of dust that remain for hours in the sky as the fragmentation products of the cosmic body, even in our day create a lasting impression on those that witness the spectacle. We can easily imagine how mysterious and terrifying to our forefathers were these fireballs which were given such names as "fire snakes," "dragons," and the like.

The largest meteoric bodies that produce fireballs fall to earth as stony and iron fragments. These fragments are called meteorites. Studies of the structure and chemical composition of meteorites provide us with exceedingly important information concerning the nature of matter in the solar system.

Summarizing, we may say that a *meteoroid* (or meteoric body) is a fragment of solid cosmic matter that collides with the earth; the word *meteor* is used to designate both the phenomenon (light) observed in the terrestrial atmosphere when a meteoroid enters it and also the particle itself, while the term *meteorite* is reserved for meteoric bodies that reach the earth. This terminology has meaning as long as we regard meteoroids in their interaction with the earth; however, when we study meteoroids in cosmic space, there is no necessity to use all these terms that define only the interaction of these bodies with the earth at times of collision. Here I shall follow the practice established in scientific literature and call meteoroids in cosmic space simply *meteors* when it is not necessary to specify this concept.

On certain days of the year we observe a phenomenon known as *meteor showers*—a large number of meteors emerging from a single part of the sky. Meteor showers usually get their names from the constellation from which they appear to be emanating.

The study of meteorites that fall to earth, and of meteors that end their existence in the atmosphere is of great importance to modern science. The huge cloud of meteoric matter that surrounds the sun is composed of a whole range

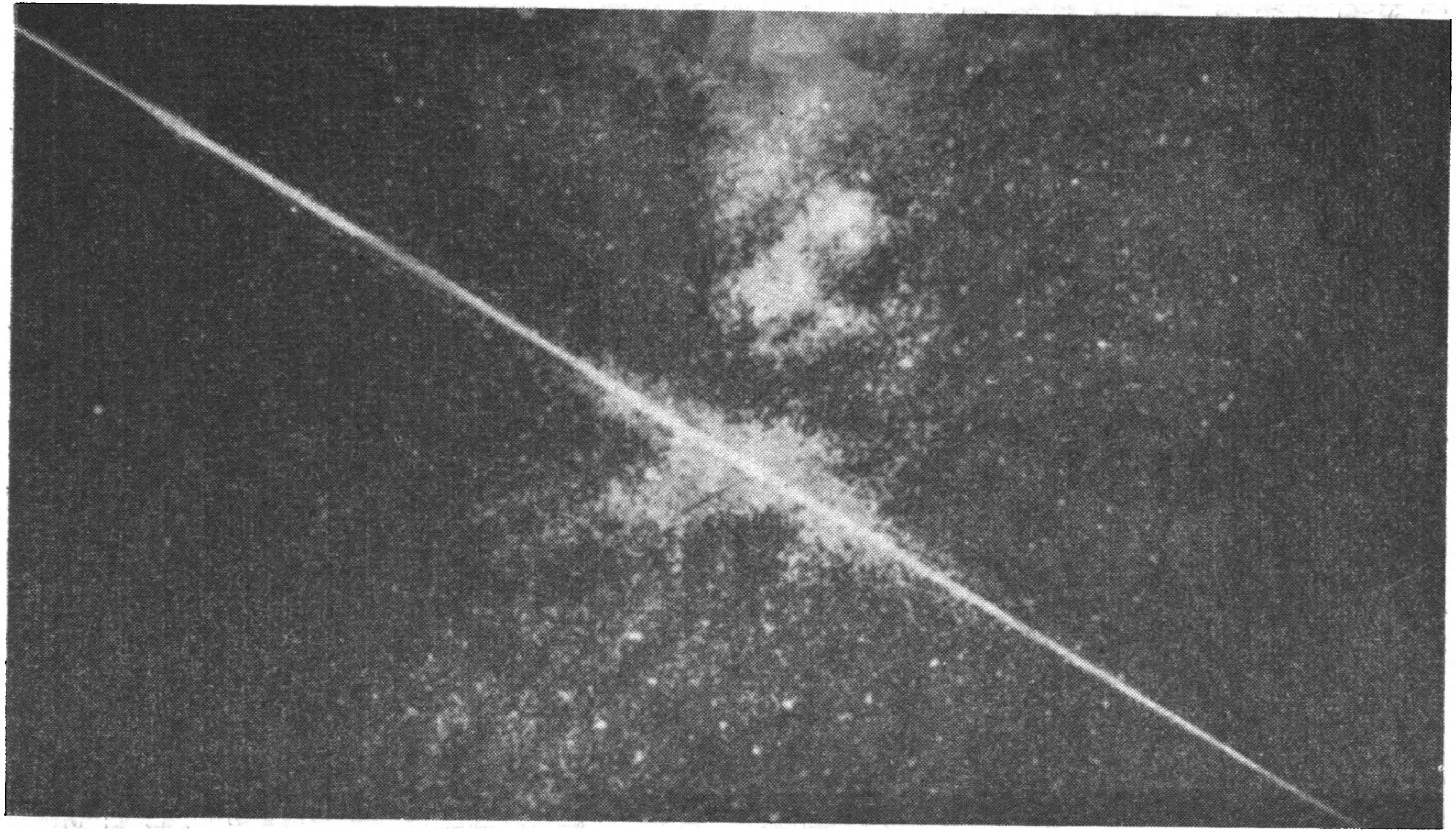


Fig. 1. A bright meteor surrounded by a column of ionized gas

of sizes from huge meteoritic chunks of material to minute meteoric dust particles. This cloud is the medium in which the earth continually moves. It is through this medium that artificial earth satellites and high-altitude research rockets hurtle. And the time is not far off when the meteor cloud will be pierced by the first interplanetary ships. Information about the structure, and the history of the development of this meteor cloud throws light on the past and future of the solar system, it helps us to understand the origin and development of the planets, including the earth we live on. Thus, the science of meteors, or meteor astronomy, is of both scientific and educational interest. This explains the birth and rapid growth of meteor astronomy as a separate branch of scientific knowledge in the nineteenth and especially the twentieth centuries.

A little over 30 years has passed since geophysicists began to take an interest in meteors. It turned out that meteor studies yield very important facts about the upper layers of the atmosphere, the physical state of these strata, about air currents at high altitudes, and the tides produced by the moon and the sun in our terrestrial ocean of air. This information is not only of theoretical interest but of practical value too. At present, high-altitude rockets move through those layers of the atmosphere that are most frequented by meteors. The recently launched artificial satellites of the earth and the future interplanetary rocket ships that will pass through the stratosphere out into space are concerned with meteors too. Engineers designing cosmic ships will have to see that they are protected from encounters with meteors.

Thus, at present meteors are the object of attention and close study of astronomers, geophysicists, and engineers. The aim of this booklet is to give the reader some idea of the present state of the science of meteors.

1. THE SCIENCE OF METEORS—AN HISTORICAL SURVEY

Meteors have been known to man since ancient times. The first documentary records of meteors were found on an ancient Egyptian papyrus written at about 2000 B. C. It is now preserved in the Leningrad Hermitage. The legends and tales of many peoples reflect the primitive views and beliefs connected with the unheralded apparition of fireballs, the flight of meteors and the falling of "stones from the sky." A Greek myth tells how Phaethon stole the fiery horses of his father Helios (the Sun), drove the flaming chariot across the sky and then fell to earth in the form of a huge stone. Actually, this is a poetical narrative of the flight of a huge fireball that ended in the fall of a meteorite. The myth about Phaethon has much in common with the legends of the North American Indians who in far-off times had witnessed the falling of a gigantic meteorite in the Arizona desert and had passed on from generation to generation the legend of the fire god come to earth. In Arabian legends, the Arabian Nights, we find shooting stars mentioned as darts of fire which the angels hurl at demons. Showers of stars are first mentioned in Chinese annals as early as 1768 B. C., and since that time they appear in the numerous annals of China, Korea, Ancient Russia (Rus), and the countries of Western Europe.

Diogenes of Apollonia, a Greek philosopher of the fourth century B.C., first correctly surmised that meteors are cosmic bodies and that they are "invisible stars that fall to earth and die out like the fiery stony star that fell near the Egos-Potamos River." True, this opinion did not become generally accepted. Together with Aristotle, the majority of the ancient, and later the mediaeval, philosophers and men of learning considered meteors to be a purely atmospheric phenomenon that arises during the ignition of terrestrial emanations when the latter move upwards and approach the fiery sphere of the sun. The huge rock near the

Egos-Potamos River, which was probably actually a meteorite, Aristotle considered to be a stone of terrestrial origin.

The Chinese annals of the ninth-eleventh centuries A. D. report observations of meteors in rather considerable detail. In modern times, these annals were first subjected to scientific analysis by the Soviet astronomer I. Astapovich. It was learned that nearly a thousand years ago many of the now active meteor showers were observed, but since then some streams have vanished entirely. In the old Russian annals, a fireball is first mentioned in the year 1091. In 1202 there is mention of the magnificent Leonid meteor shower. Russian annals give a rather detailed description of the stony shower of June 25, 1290, near the town of Ustyug Veliky. The falling of meteorites that day was attended by a huge and extremely brilliant fireball, by loud reports and quaking of the earth. The woods in the region of Kotovalov Ves suffered greatly from the flight of the fireball and the falling of stony fragments. On May 19, 1421, from Novgorod Veliky came reports of a bright fireball accompanied by powerful sound phenomena and the falling of a swarm of stony meteorites. And these are not the only records.

Despite the gradual accumulation of such facts, for nearly two thousand years men's views on meteoric phenomena did not undergo any essential changes. Following a centuries-long period of stagnation in the development of astronomy meteors were again brought to the forefront of attention at the end of the seventeenth century. In England, in 1686, Halley computed the trajectory of a bright fireball and advanced the view that this phenomenon was caused by a meteoric body of cosmic origin.

In Russia, observations of meteors (and other atmospheric phenomena too) were begun in St. Petersburg by I. Gmelin, G. Kraft, A. Tatishchev in 1734.

The end of the eighteenth century may be regarded as the beginning of meteor astronomy. In 1794, E. Khladny, Corresponding Member of the St. Petersburg Academy of

Sciences, demonstrated convincingly that meteorites fall to earth from interplanetary space. In 1798, two German students, Brandes and Benzenberg, were the first to determine the heights of meteors on the basis of simultaneous observations from two distant points. During his trip to South America in 1799, Humboldt observed a shower of the Leonid meteor stream and from talks with old-timers among the Indians he learned that such showers of "stars" had been observed in 1733 and 1766. From this he deduced a periodicity of 33 years for the Leonids. In 1832, the eastern hemisphere saw a splendid Leonid meteor shower, and in 1833, a beautiful display was observed in the western hemisphere. In 1832, a self-taught astronomer from Kursk, F. Semyonov, observed the Leonids and discovered the phenomenon of radiation of meteors, which is due to the apparent divergence (in perspective) of their paths, though in reality they are parallel in space. He also expressed the view that meteors might be connected with comets. In 1833, independently of Semyonov, the radiation of meteors was discovered by many observers in Western Europe and North America.

The meteor showers of 1799 and 1832-33 evoked great interest in scientific circles and made the French astronomers Arago and Biot take up the study of Chinese, Korean, and Japanese annals. It was found that the Leonid meteor shower had been observed for more than 3,500 years at periods of 33 years. The orbit of the Leonid swarm in the solar system was computed, and it appeared to be similar to the orbits of some of the big comets. However, proof of the intimate relationship between comets and meteors was to come much later.

In Russia, the first systematic observations of meteors were begun in 1852 by Shveitser at the Astronomical Observatory of the Moscow University, and later by Gusev in Vilno. In 1862, Bredikhin, in a paper entitled "On Cometary Tails," summarized the results of Russian and foreign observations of comets and meteors and expressed the

view that meteor streams might be ejected from comets. In 1865-66, mass-scale routine observations of meteors were begun in England by Denning, in Italy by Schiaparelli, in the U.S.A. by Newton, and in other countries. This heightened interest in meteors during these years was due to the expected return of the Leonid shower.

The Leonids did not disappoint astronomers and in 1866-68 produced a marvellous display. In 1866, Schiaparelli established a genetic connection between the Leonid and Perseid meteor streams and comets and hypothesized the disintegration of comets under the action of solar attraction. Meanwhile, Bredikhin was developing his own ideas and by 1881 had completed a theory of the ejection of meteoric particles from cometary nuclei. The ideas developed by Schiaparelli and Bredikhin are to this day the basis of all studies dealing with interrelations between comets and meteor streams.

In 1882, Kleiber wrote the first Russian monograph on meteors published two years later in St. Petersburg.

At the end of the nineteenth century up-to-date astrophysical methods began to be used in meteor studies. The first photograph of a meteor was obtained in Prague in 1885. In 1893, Elkin at the Yale Observatory in the U. S. A. and, independently, Sternberg at the Moscow University Astronomical Observatory, applied a rotating shutter to determine the angular velocity of meteors. Much later, in the 1930's, this method of determining meteor velocities found wide application and is still used. In 1901, Sikora in Tashkent was the first in Russia to organize systematic photography of meteors. In 1904, Blazhko obtained the first spectrogram of a meteor at the Moscow University Astronomical Observatory.

Beginning with the 1920's interest in meteors greatly increased in connection with studies of the upper layers of the atmosphere. This period coincides with the rapid development of Soviet meteor astronomy. During the past thirty odd years Soviet science has made great strides in me-

teor research. The first collective efforts of Soviet astronomy amateurs in meteor studies got under way in 1921. This work has been going on successfully to the present day. In 1925, Astapovich worked out an extensive programme of meteor studies and began routine observations. This remarkable series of observations covered a period of over 25 years and, together with a similar series of observations carried out by Maltsev, Sytinskaya and other Soviet observers, as well as those of Denning (England) and Hoffmeister (Germany), represents an extremely valuable contribution to our knowledge of the nature of meteors.

In the U.S.S.R., from 1925 on, a number of special expeditions for meteor studies were sent to the southern part of the country (the Caucasus and Central Asia) where climatic conditions are favourable for obtaining extensive factual material. The first scientific conference on the study of comets and meteors was held in 1935. Since then Soviet investigators of comets and meteors have met many times to discuss their work. During recent years, conferences were held in Kiev (1951), Stalinabad (1952), and Odessa (1955, 1957).

Soviet scientists have done much interesting and important work in meteor astronomy. The attainments of Soviet scientists in meteor astronomy are in large measure an indication of the present-day level of the subject.

During the past 30-35 years, this branch of astronomy has also undergone a rapid development in other countries. Meteor associations have sprung up in England, Czechoslovakia, the U.S.A., Canada and New Zealand.

One of the most important problems whose solution has been sought, since the 1920's, in a large number of studies both in the U.S.S.R. and in other countries is that of the interaction of meteoroids and the atmosphere and a study of atmospheric structure from meteor observations.

As early as 1923, Lindemann and Dobson in England applied an approximate physical theory of meteors to the study of the structure of the upper layers of the atmosphere.

In 1931, N. Ivanov, a Soviet radio engineer and amateur astronomer, published a paper in which, on the basis of experimental data, a correlation was established for the first time between meteoric phenomena and ionization of the terrestrial atmosphere. That same year, observations were conducted in the U.S.A. that established the same relationship between these two phenomena.

In 1935, the author together with Stanyukovich laid the foundation for the study of physical conditions in the upper atmosphere from meteor photographs. A special photographic meteor patrol was begun in 1938 at the Stalinabad Astronomical Observatory, now reorganized into the Institute of Astrophysics of the Academy of Sciences of the Tajik S.S.R. In 1956, the meteor patrol of the Institute of Astrophysics in Stalinabad was considerably improved, and in 1957, in connection with the International Geophysical Year, new meteor patrols were established in the Institute of Physics and Geophysics at Ashkhabad and at the astronomical observatories at the universities of Kiev and Odessa.

Systematic photographic studies of meteors were begun at the Harvard Observatory (U.S.A.) in 1936 under the leadership of F. Whipple and, later, also Jacchia and other investigators. Exceedingly important results were produced. Special credit goes to American investigators for the development and application of new superhigh-speed cameras that make it possible to photograph faint meteors, i.e., practically all those that are detected by the unaided eye. The observational data obtained were used to compile tables of the state of the upper layers of the atmosphere up to 120 kilometres (density, temperature, etc.). It was found that on the one hand there are dense, mechanically very firm meteoric bodies, and, on the other, a whole class of loose bodies that easily break up in their passage through the upper atmosphere, which to some extent resembles the flight of snowflakes through the air.

A very detailed physical theory of meteor flights in the atmosphere was developed by Levin. A summary of this work was recently published (1957) by the author in a special monograph. At the present time, many scientists are working on the physical theory of meteors.

A second important problem that has engaged the attention of researchers during the past 25 years is the nature of the meteoric bodies themselves. In this respect very important is the obtaining of meteoric spectra that tell us about their chemical composition.

In 1932, Millman (Canada) published the first survey of meteoric spectra and since that time has been successfully engaged with his associates in the study of meteoric spectra with prismatic and diffraction spectrographs.

Since 1934 the U.S.S.R. too has been successfully developing spectrographic methods in meteor studies.

Studies of meteor glow have been in progress in the U.S.S.R. since 1935. They were begun by Sytinskaya who in 1940 worked out a method of determining the meteoric mass from the brightness.

Systematic and fruitful visual and photographic observations are carried out in Czechoslovakia at the astronomical observatory in Ondřejov and at other places. Important work on the nature of meteoric bodies and meteor showers and also on methods of study has been carried out in Czechoslovakia by Guth, Link, Plavec, and Ceplecha. We must also note the many years of systematic meteor investigation carried out by Hoffmeister in Germany and in Southern Africa that have produced interesting results.

One of the latest methods in meteor studies that has produced a great range of results is the radar technique.

Radar was first used for meteor observations in 1945 by Hey and Stewart in England. Regular radar studies of meteors were organized in 1946 with the participation of Blackett and Appleton. A huge modern radio observatory has been created near Manchester—the Jodrell Bank Experimental Station of the University of Manchester headed

by Lovell. Meteor studies here are conducted both night and day in any weather, often in fog and rain.

In 1946, Chechik and Levin carried out the first Soviet radar observations of the Draconid meteor shower and since 1957 such observations have been in progress at stations in Kazan, Kharkov, Tomsk, Stalinabad, and elsewhere in accordance with the programme of the International Geophysical Year. Particularly outstanding results in radio observations of meteors have been obtained by a group of workers of the Kharkov Polytechnic Institute under B. Kashcheyev. Besides England and the U.S.S.R., radio observations of meteors are conducted in Czechoslovakia at the Observatory at Ondřejov, in Canada, where an extensive series of observations has been undertaken by Millman and McKinley, in Australia, India, New Zealand, the U.S.A., Sweden and Japan. Everywhere, radio observations of meteors are now providing the principal factual material, which when linked up with visual and photographic observations helps us to learn more about meteoric matter and its interaction with the earth.

The International Geophysical Year (1957-1958) posed to meteor workers a series of special problems, chief among them being that of the action of meteoric bombardment on the state of the ionosphere. This called for international observations of meteors which during this period were organized according to a special programme. Particularly active in this respect were the Soviet Union and Canada. At the same time, the launching of the Soviet and American artificial earth satellites made it possible to begin a direct study of the density of the meteor cloud in the environs of the earth by means of recording the impacts made by minute meteoric bodies (micrometeorites) on special sensing devices carried by the satellites. This greatly extended the potentialities of the science of meteors.

At present, meteor astronomy is a rapidly developing branch of science on the border-line of astronomy, geophys-

ics, and radiophysics. The principal problems of modern meteor astronomy are: 1) the penetration of meteors into the terrestrial atmosphere, 2) the study of meteoric matter, its motion and development in cosmic space, 3) the role played by meteors in the origin and development of the solar system.

Soviet scientists are taking an active part in the solution of all these problems, utilizing the traditions and rich experience of Russian science and exchanging their attainments with the scientists of other countries.

2. MODERN METHODS OF STUDYING METEORS

Meteors are observed visually, and through the use of photographic and radio techniques.

Visual observations of meteors with the unaided eye were the only reliable method in meteor astronomy during the nineteenth and the beginning of the twentieth centuries and to this day are still important. On a clear moonless night an observer can detect meteors of the fifth and even sixth magnitude, which is the brightness of the faintest stars visible to the naked eye.* In one hour of observing he should be able to detect an average of 10 meteors. The unaided eye usually records meteors of the first to the fourth magnitude. Brighter meteors are comparatively rare, while only a few of the considerable number of fainter meteors are picked up by the eye.

The apparent trajectory of a meteor among the stars may be registered on a star map with some degree of accuracy. If the paths of meteors that have been thus recorded are traced backward, it will be noticed that they appear to emanate from small areas (Fig. 2). These meteors belong to one and the same stream and in interplanetary space

* In astronomy the term magnitude denotes the apparent brightness of stars. Very bright stars are of first magnitude, the faintest naked-eye stars—sixth magnitude. Meteor brightnesses are distinguished by the same scale.

Fig. 2. Meteor paths traced on a star map. Observations of the Draconid meteor shower of October 9, 1933. The radiant of the Draconids is shown encircled

move in parallel paths. Such areas, with diameters of several degrees, are known as the *radiants* of meteor showers. A determination of the apparent position of radiants in the sky is necessary for studying the motion of meteoroids in the solar system and constitutes one of the most important tasks of visual meteor observations. Apart from locating radiants, the pinpointing of meteors on star maps is helpful in determining meteor heights through observations at two distant points.

It is very important to know the chief physical peculiarities of meteors—their brightness, colour, velocity, clarity of outline, the presence of flares, trail, etc. Most of these characteristics make it possible to determine indirectly the speed of motion of meteors in interplanetary space. A very detailed programme of visual study of the physical properties of meteors was worked out and put into practice over a number of years by Astapovich in Ashkhabad (a so-called maximum programme). Of greatest value are collective visual observations of meteors, even if they are conducted by amateurs who are not so experienced, as, for instance, a group of observers of the All-Union Astronomical-Geodetical Society in Simferopol who during the International Geophysical Year carried out an extremely valuable series of visual observations.

The principal shortcomings of visual observations are that they demand a great deal of time and energy, and the results are not very accurate. However, the suddenness with which meteors make their appearance and the difficulty of applying instrumental methods of observation for a long time made visual observations the chief method for meteor studies. Even today, much of the information about meteors is gained from visual observations.

Meteors can also be observed by means of binoculars or fast short-focus telescopes with a large field of view. This permits of a more precise determination of their apparent trajectories, heights, and coordinates of the radiants, and

also of detecting fainter meteors that are invisible to the naked eye. Ordinarily, small telescopes permit observation of meteors of 11th and 12th magnitude.

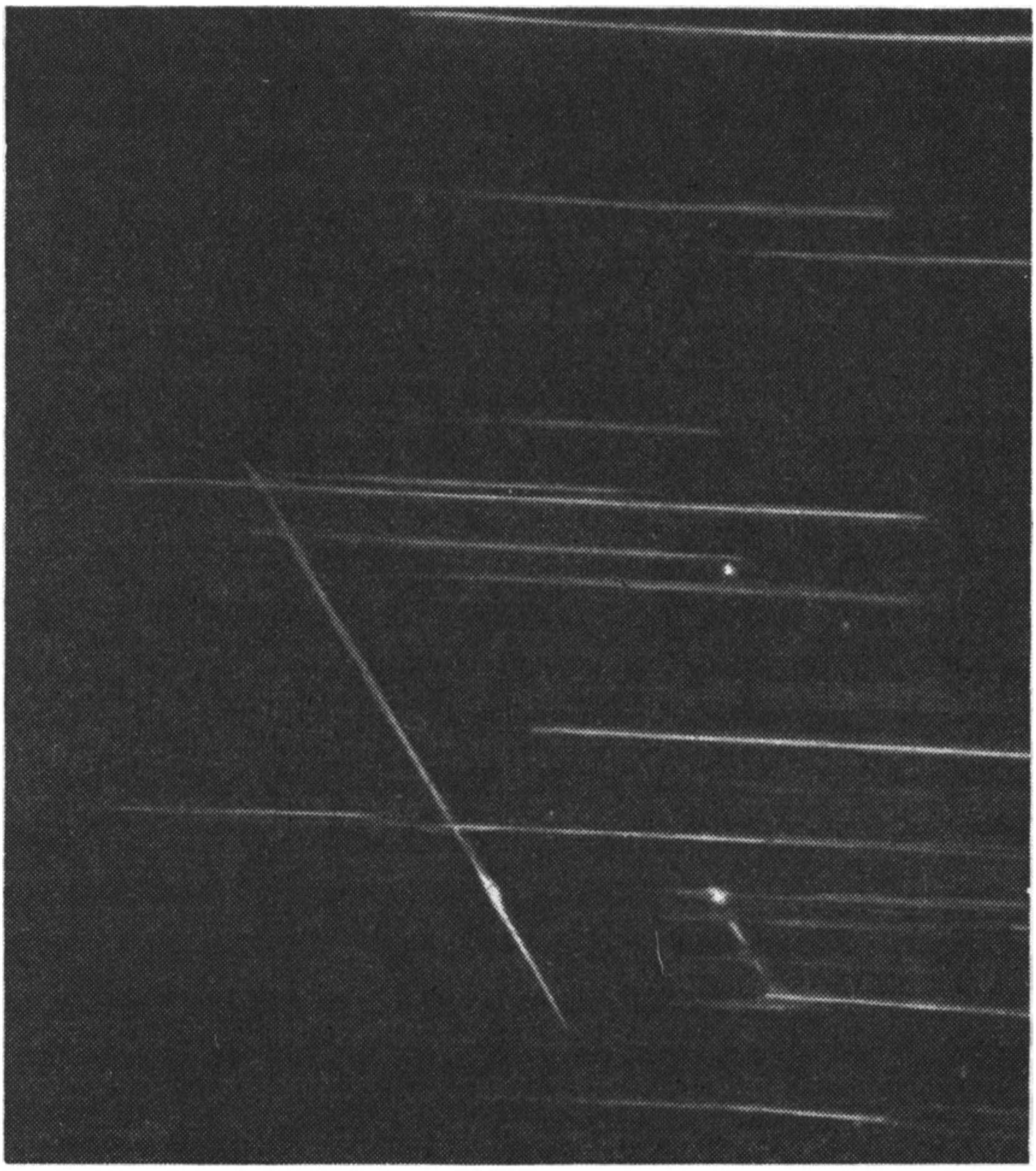


Fig. 3. A meteor photographed at two spaced points. This is a combined photograph made at Ashkhabad and Vannovskoye spaced 25 km. The right hand photo was made through a rotating shutter

Photography has become an effective tool in meteor studies during the past 20 years due to the advent of fast short-focus cameras with large fields of view and highly sensitive emulsions. Meteors are sometimes photographed by chance in parts of the sky that are being studied for other purposes. Such photographs may be used to study

the flight of meteors through the atmosphere, but to solve fundamental problems in the meteor field one requires a special organization of photography through the use of short-focus cameras at two points distant from one another five to forty kilometres. Such double-camera techniques make it possible to determine the heights and velocities of meteors. The objectives are left open for several hours, and traces are left on the plates by all sufficiently bright meteors that pass through the field of view of the cameras (Fig. 3).

To determine the velocity of a meteor, use is made of a rotating shutter in front of the objective. A rotating shutter driven by a synchronous motor occults the objective several dozen times a second with the result that the meteor trails in the photograph come out as segmented lines (Fig. 3, to the right.) If we know the length of each segment and the speed of the rotating shutter, it is possible to determine the rate of motion of the meteor in space.

Unfortunately, meteor photographic techniques are not very effective. Even with highly sensitive photographic plates and films, as much as 50 to 100 hours of exposure time has to be spent with a single camera to record one meteor. One way of improving upon this situation is to connect several cameras into one unit that covers a greater area of the sky. Two such units, one of which is equipped with a rotating shutter, comprise what is known as a meteor patrol. As mentioned earlier, such patrols have been set up at Stalinabad, Ashkhabad, Kiev and Odessa in the U.S.S.R. Meteor patrols are in operation in Czechoslovakia, at the Skalnaté Pleso Observatory, and in the U.S.A. (Harvard Observatory). During recent years the American patrol has been perfected by a radical increase in the aperture ratio of the cameras. The use of Schmidt mirror-lens systems at F/0.7 and curved film in the focus has made it possible to record meteors down to fifth magnitude, whereas it is not ordinarily possible to photograph meteors fainter than second magnitude.

Using these cameras, Whipple has succeeded in recording the ionized trails of very bright meteors. To photograph these trails, the observer on duty quickly sets the camera in that part of the sky where a bright meteor has just passed and makes several 2-second exposures in succession with intervals of 10 seconds. In the process, the camera is automatically shifted each time so that the trail images on the photograph do not overlap. Such photographs permit us to determine, from the drift of the meteor trails, the direction and rate of motion of the wind in the upper atmosphere, and also to follow changes in the shape of the trail by determining the rate at which it disperses and the rate of diminishing glow. All this helps us to understand the physical structure of the upper atmosphere.

A thing more difficult than photographing meteors is recording their spectra. To date, only several score spectra have been obtained in the whole world. A meteor spectrum is obtained by means of a prism placed in front of a fast objective. This type of prismatic camera, first used a half century ago by S. Blazhko, was for a long time the chief instrument for this purpose. Millman (Canada) recently used a camera with a diffraction grating in front of the objective for spectrographing meteors. A diffraction grating, it will be recalled, is like a prism in that it, too, disperses white light into a spectrum.

Usually, a meteor spectrum consists of a series of individual lines of chemical elements that comprise the meteor, and each line depicts the meteor as if it consisted only of the given element. Naturally, a meteor image in the light of some one element is much fainter than its complete picture on an ordinary photograph. For this reason, small high-speed, short-focus cameras are used to photograph meteoric spectra. Since the spectra in the photographs are very small, one cannot speak of a precise identification of all spectral lines. The spectral lines are identified in whole groups by their mutual positions, intensity, and so forth.

Undoubtedly, the most powerful modern tool in the study of meteors is radar. The development of radar techniques during recent years has placed this far-seeing tool at the disposal of astronomers for meteor observations. Meteors can now be observed during the daytime, in foggy and rainy weather, round the clock. Meteors are observed with ordinary radar sets operating on wavelengths from four to twelve metres. Radar, it will be recalled, is able to measure the distance to a target that re-

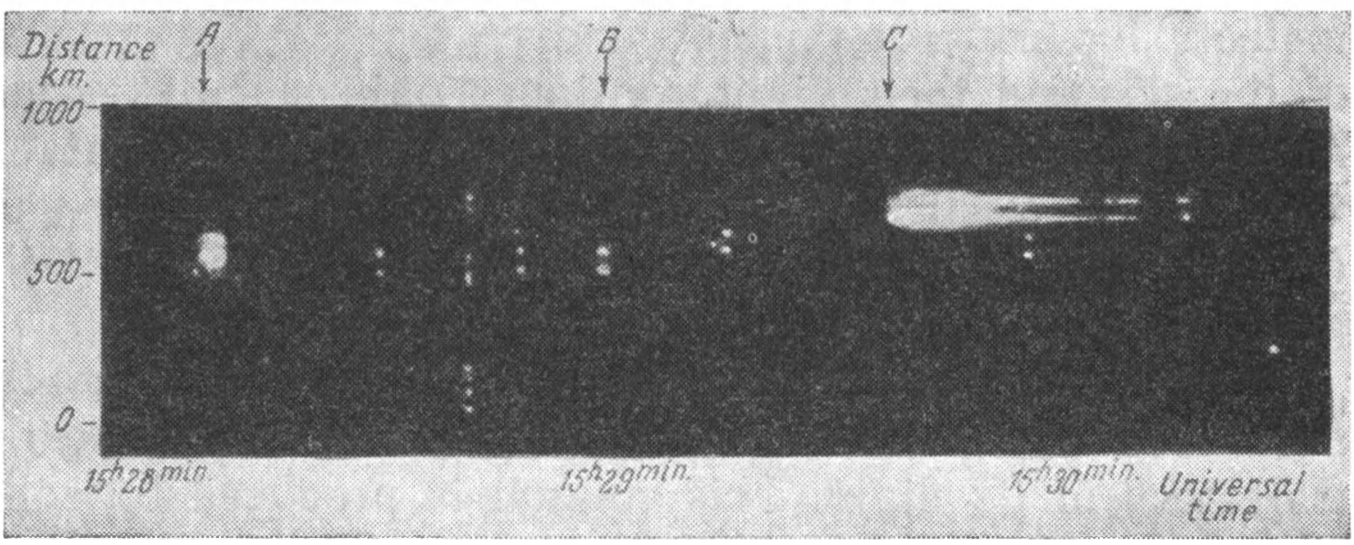


Fig. 4. Radio-location of meteors. A, B, C are meteor radio echoes

flects radio waves by determining the time that it takes them to reach the target and return. This is possible because the speed of propagation of the waves is known (300,000 km./sec.).

The principal component in the receiving part of the radar set is the familiar cathode-ray tube of television. In the cathode-ray tube, the radio waves reflected from the target are converted into a stream of electrons—an electron beam that produces a bright spot on the luminescent radar screen. The position of this spot on the screen depends on the travel time of the radio waves, i.e., in the final analysis, on the distance to the target (Fig. 4).

The pulses (signals) emitted by the radar aerial propagate mainly in a single direction, and their intensity

rapidly diminishes with any deviation from this direction. If a diagram of signal intensity according to direction is constructed, it will consist entirely of lobes, so-called lobes of aerial directivity. One of these is known as the major lobe. These lobes cut out sections of the sky in which it is thus possible to record the flight of meteors.

If the range scale on the screen of the cathode-ray tube is calibrated in kilometres, we can read off directly the distance to the target, which in our case is a meteor. It is impossible beforehand to orientate the aerial on the meteor, for meteors appear unexpectedly in any portion of the sky and their flight continues only a split second. And so the radar aerial is either fixed in place or is rotated slowly on a vertical axis so that it can scan the sky in different directions. Meteors that enter the field of the aerial lobe produce a radio echo.

The immediate reason for the reflection of the radar pulse is a column of gas ionized by the meteor along the trajectory of its flight. This column is produced by collisions of particles of air with the meteor in its flight through the atmosphere at speeds from 10 to 70 km./sec. This is quite sufficient to cause ionization, that is, a separation of the molecules and atoms of air and the meteor into positively and negatively charged particles of electricity. The diameter of the column of ionized gas is measured in metres and increases in time due to dispersion (diffusion) of the gases. Its length is reckoned in tens of kilometres. A column of ionized gas of this type is capable of reflecting radio waves and creating radio echoes until it is entirely dispersed by the stratospheric winds.

Clear radio echoes reflected perpendicularly to the trajectory of the meteor are best obtained on wavelengths of four to five metres. When longer wavelengths are used, especially in the 9-12 metre range, the picture of reflection of the radio signal becomes exceedingly complex. The reflecting power of ionized meteor trails on these wavelengths increases substantially, and spurious radio echoes

arise not only along the line perpendicular to the trajectory, but also along lines that form various angles with this perpendicular. For this reason, a wavelength of about five metres is most convenient for mass radio observations of meteors. Such observations include meteor counts, determinations of meteor distances and heights and of radiants.

The first two problems are so easily solved by radar that they do not require any special explanation.

The technique of determining radiants is based on the use of two radar sets, the aerials of which are at right angles to each other. The radio signal is reflected from the meteor along a ray perpendicular to the path of the meteor. Its radiant therefore lies in a direction 90° distant from the direction of the central ray of each of the two radars.

Thus, the two radar sets together make it possible to determine the position of the radiant in the sky.

Another method of determining radiants is suitable for some bright meteors that produce reflections along the perpendicular of their paths and also side reflections. From three stations situated at the vertices of a roughly equilateral triangle with sides of about 60 kilometres, determinations are made of the distances to two points on the meteor trail. This gives the direction of the trajectory and, hence, the radiant of the meteor.

Very important are velocity determinations of meteors by means of radar. Radar operating on eight- to ten-metre wavelengths permits obtaining non-specular reflections (i.e., lying to the side of the perpendicular radio beam) from the meteor trail. This makes it possible to follow, on the radar screen, meteor-distance variations in time. The screen of the cathode-ray tube displays a hyperbolic curve whose shape is an indication of the meteor's velocity (Fig. 5).

When a meteor passes across the area of the sky cut out by the aerial lobe, there is observed an extremely interest-

ing phenomenon known as radio-wave diffraction, which likewise permits a determination of the velocity of the meteor. At the instant the meteor appears on the perpendic-

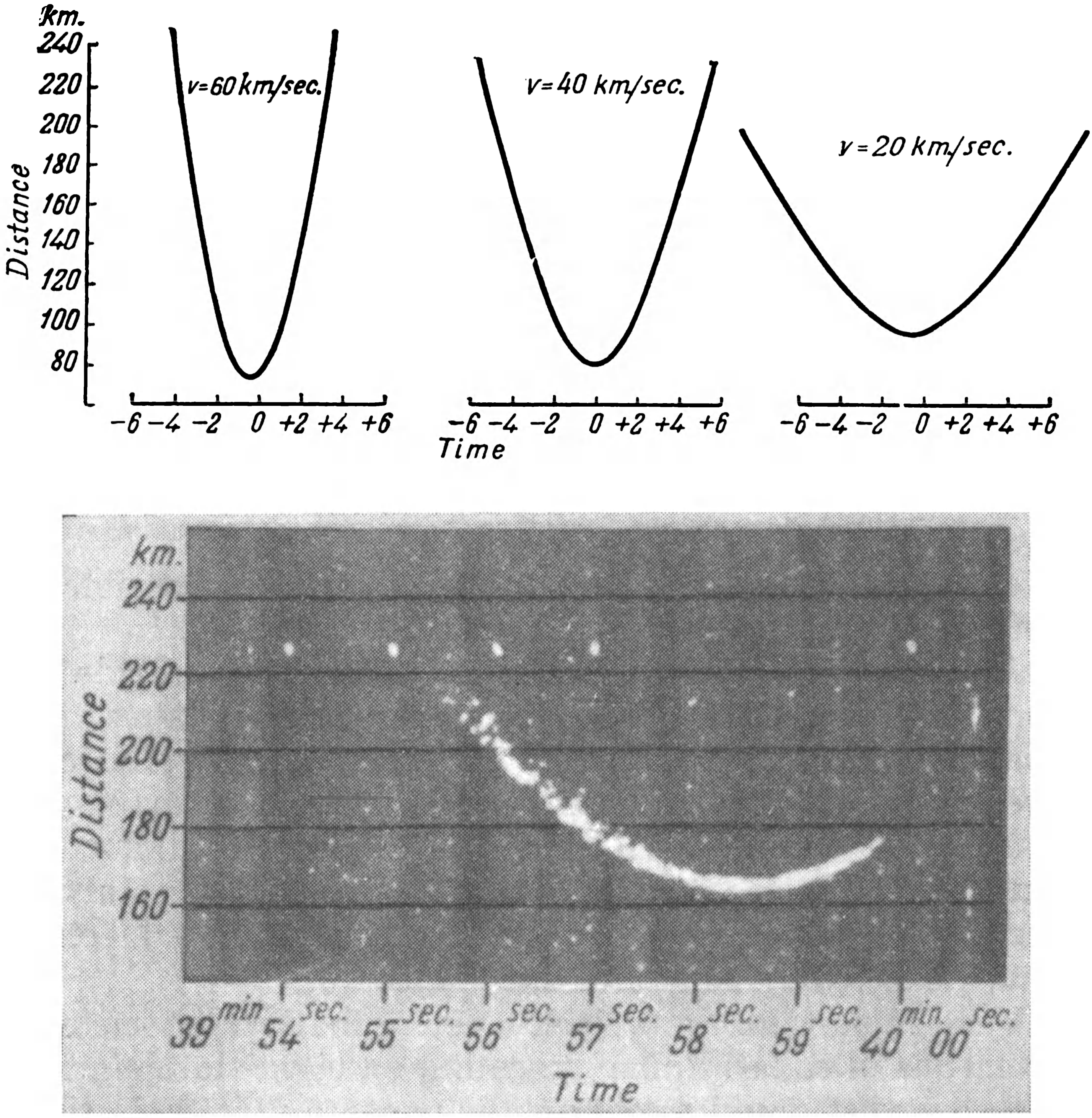


Fig. 5. Radar determination of meteor velocities. Top—shape of range-time diagram for meteors of different velocities. Bottom—same diagram on the screen of an electron-ray tube

ular ray of the aerial, the receiver records a rapidly building-up radio echo. Following this initial instant, radio waves reflected from the meteor as it moves forward

will interfere with the central reflection, that is, they will be superimposed on it and will strengthen or weaken the reflection depending on the phase difference of the two reflections (Fig. 6). And in turn, this phase difference is determined by the range difference along the central beam of the aerial and along the direction of the moving meteor.

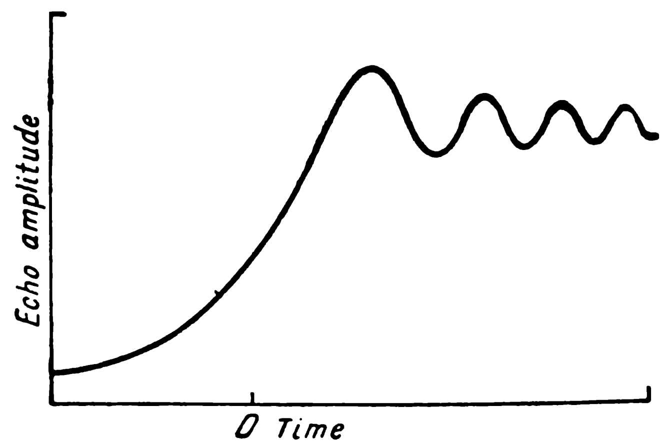


Fig. 6. Diffraction of radio waves during meteor flights

Thus, for example, if the difference in distances OB' and OP (Fig. 7) amounts to half a wavelength ($\lambda/2$), the electromagnetic oscillations from points B' and P will be in opposite phases, thus weakening the radio echo. This will also be the case if the range difference is equal to an odd number of half-waves. But if this difference is equal to an even number of half-waves (that is, to an integral number of waves), as, for example, at point D', the oscillations will arrive in the same phase as in the direction PO, and will strengthen each other. In this method, the meter velocity is determined from the time intervals between radio-echo maxima. Since the lengths of segments PB', PD', etc., are easily determined, it is not difficult to obtain also the velocity of the meteor over the entire route if we know the distance to the meteor R and the wavelength. The diffraction method permits obtaining meteor velocities with a very high accuracy, and it is applicable to approximately 20 per cent of all radar-recorded meteors.

Radio techniques have likewise made it possible to establish the presence of winds in the upper layers of the atmosphere and to determine their direction and velocity. Due to the movements of meteor trails produced by stratosphere winds, the wavelength of a reflected radio ray

diminishes with recession of the trail from the observer and increases when the trail is approaching, in complete analogy with the rising and falling pitch of a train whistle

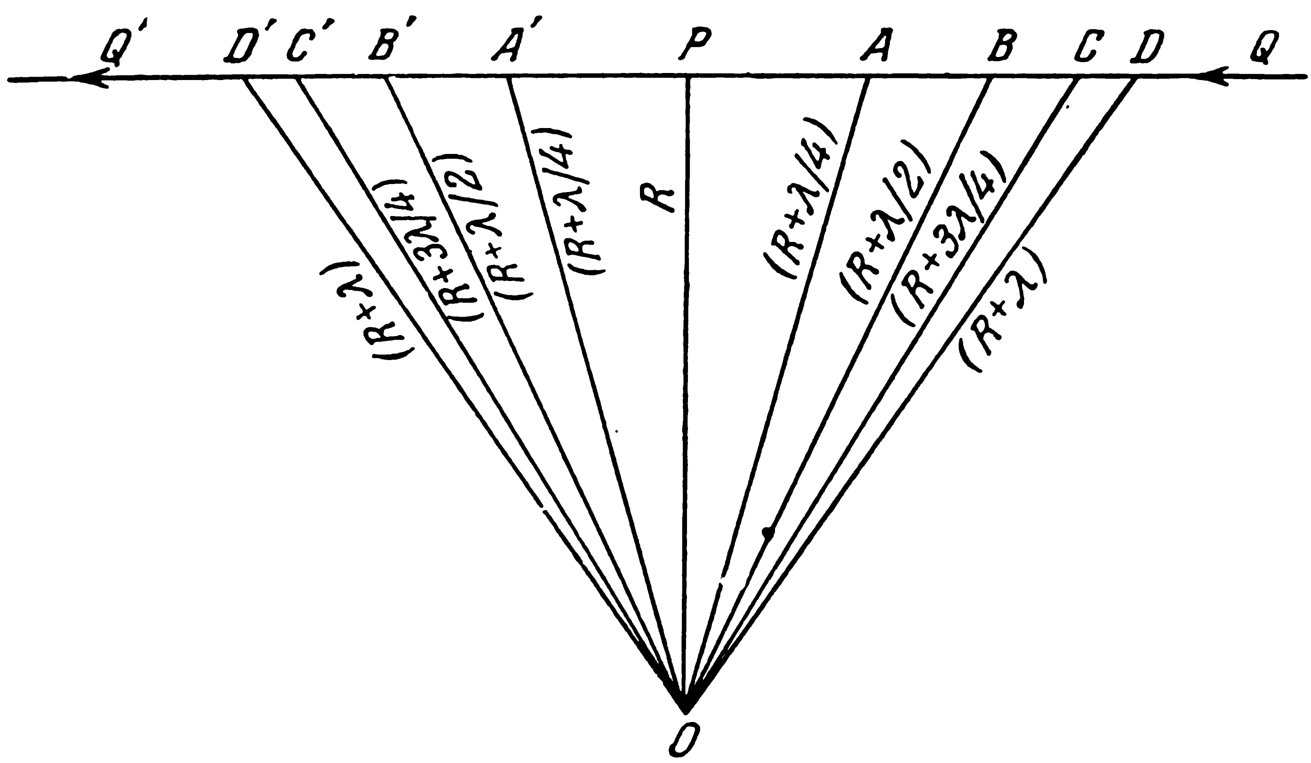


Fig. 7. An explanation of diffraction phenomena (Fresnel regions) during meteor flights. O—observer, QQ'—meteor trajectory

when the locomotive passes the observer. By observing these variations in radio wavelengths (called the Doppler effect) it is possible to determine the change in movement of a meteor trail along the line of sight.

In concluding this review of modern methods of meteor research, we may note their extreme diversity. With respect to a number of problems relating to the geophysical and astronomical aspects of meteoric phenomena, complete solutions are best attained through a composite application of different methods of investigation, one of the methods being regarded as principal and the remaining as subsidiary. This is especially important in attacking highly complex problems. At present the most important methods in meteor studies are radar and photography.

3. METEORS IN THE EARTH'S ATMOSPHERE

Meteors make their appearance at heights of 130 km. and lower and ordinarily disappear somewhere around 75 km. above the earth. These limits vary depending on the mass and velocity of the bodies that enter the atmosphere. Visual determinations of meteor heights from two or more points (so-called corresponding points) have to do chiefly

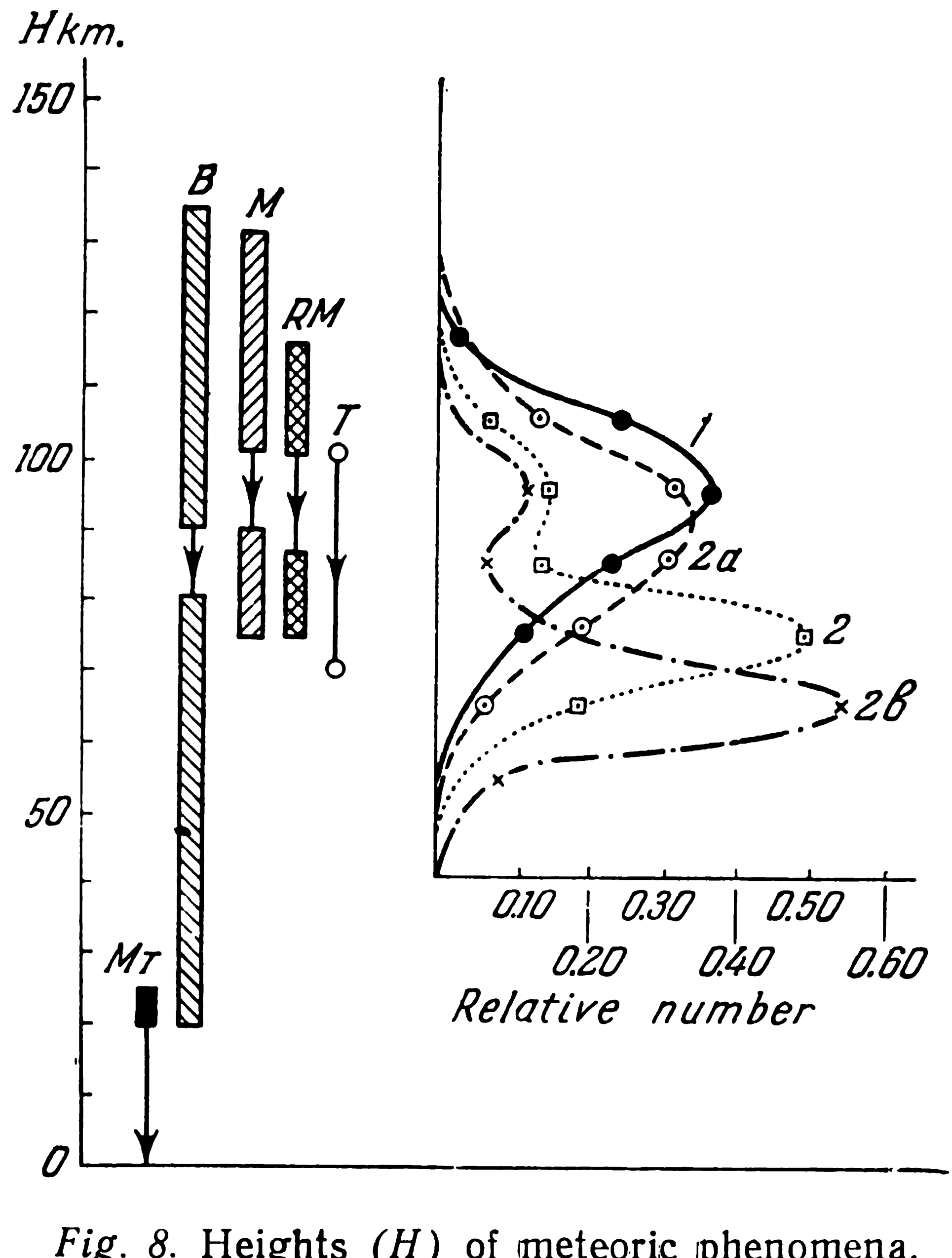


Fig. 8. Heights *(H)* of meteoric phenomena. Left, limit heights: the beginning and end of paths of bolides *(B)*, visual meteors *(M)* and radar meteors *(RM)*, telescopic meteors in visual observations *(T)*: (M_T) is the delay region of meteorites. Right, distribution curves: *1*—middle of meteor paths according to radar observations, *2*—the same for photographic data, *2a* and *2b*—the beginning and end of path according to photographic data

with meteors of zero to third magnitude. With allowance made for rather considerable errors, visual observations give the following meteor heights: appearance $H_1=130\text{-}100$ km., disappearance $H_2=90\text{-}75$ km., height in middle of path $H_0=110\text{-}90$ km. (Fig. 8).

The far more accurate photographic determinations of heights are, as a rule, made for bright meteors of from minus fifth to second magnitude or for the brightest parts of their trajectories. Photographic observations in the U.S.S.R. give heights for bright meteors within the following limits: $H_1=110\text{-}68$ km., $H_2=100\text{-}55$ km., $H_0=105\text{-}60$ km. Radar observations yield H_1 and H_2 separately only for the very brightest meteors. The results are $H_1=115\text{-}100$ km., $H_2=85\text{-}75$ km. It must be noted that radar determinations of meteor heights refer only to that part of the trajectory that produces a sufficiently intensive ionization trail. For this reason, one and the same meteor may have a photographic height that differs perceptibly from the radar height.

As regards fainter meteors, radar yields only statistically mean heights. A distribution of average heights for meteors chiefly of magnitude one to six obtained by radar is given below:

Height	120-111	110-101	100-91	90-81	80-71 km.
Percentage of determinations .	2	25	37	24	12

An examination of all the data on meteor heights shows that the overwhelming majority of meteors are observed between 110 and 80 km. above the earth. This zone is the same for telescopic meteors, which according to A. Bakharev have the following heights: $H_1=100$ km., $H_2=70$ km. However, the telescopic observations of Astapovich and his co-workers in Ashkhabad indicate that a considerable number of telescopic meteors is observed below 75 km.,

chiefly between 60 and 40 km. Apparently, these are slow and therefore faint meteors which begin to glow only after they have dug deep into the terrestrial atmosphere.

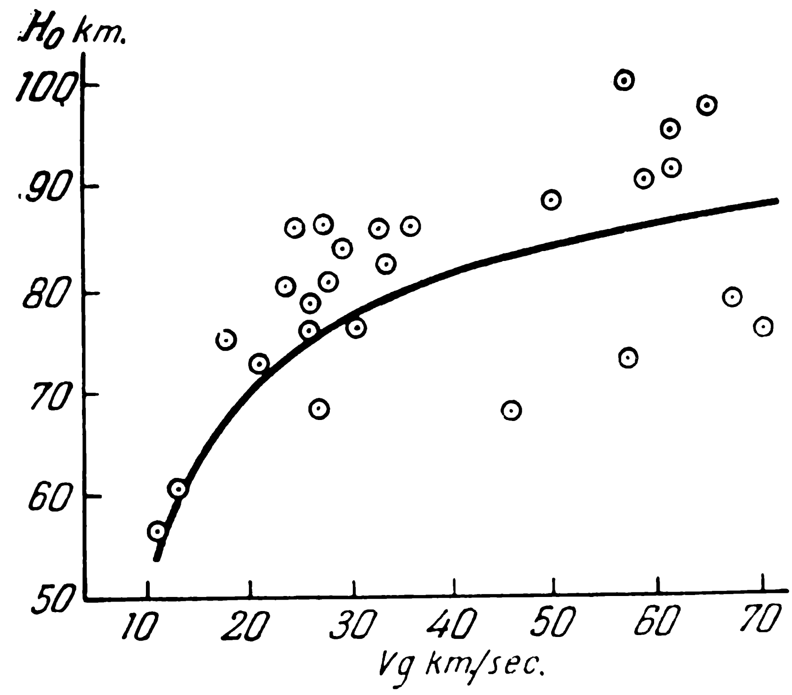


Fig. 9. The mean height (H) as a function of the geocentric velocity V_g of meteors taken from photographic determinations

Speaking of very large bodies, we find that fireballs make their appearance at heights H_1=135-90 km., with the height of the end point of their path H_2=80-20 km. Fireballs that penetrate down to 55 km. are accompanied by sound effects, and those that reach down to 25-20 km. usually drop meteorites.

The heights of meteors depend not only on their masses but also on their velocities relative to the earth, i.e., their so-called geocentric velocities. The greater the velocity of the meteor the higher up it begins to glow, the reason being that a fast meteor makes many more collisions with the particles of air than does a slow meteor. And the effect is apparent even in the tenuous upper atmosphere. The average heights of meteors are shown in Fig. 9 as a function of their geocentric velocities. They are related as follows:

Geocentric velocity (V_g)	20	30	40	50	60	70	km./sec.
Average height (H_o)	68	77	82	85	87	90	km.

For one and the same geocentric velocity the height of the meteor depends on its mass. The greater the mass the deeper it penetrates.

The visible part of a meteor trajectory, that is, the length of its path in the atmosphere, is determined by the

heights of its appearance and disappearance, and also the inclination of its trajectory to the horizon. The steeper this inclination the shorter the visible path length. The path lengths of ordinary meteors do not, as a rule, exceed several tens of kilometres, but in the case of very bright

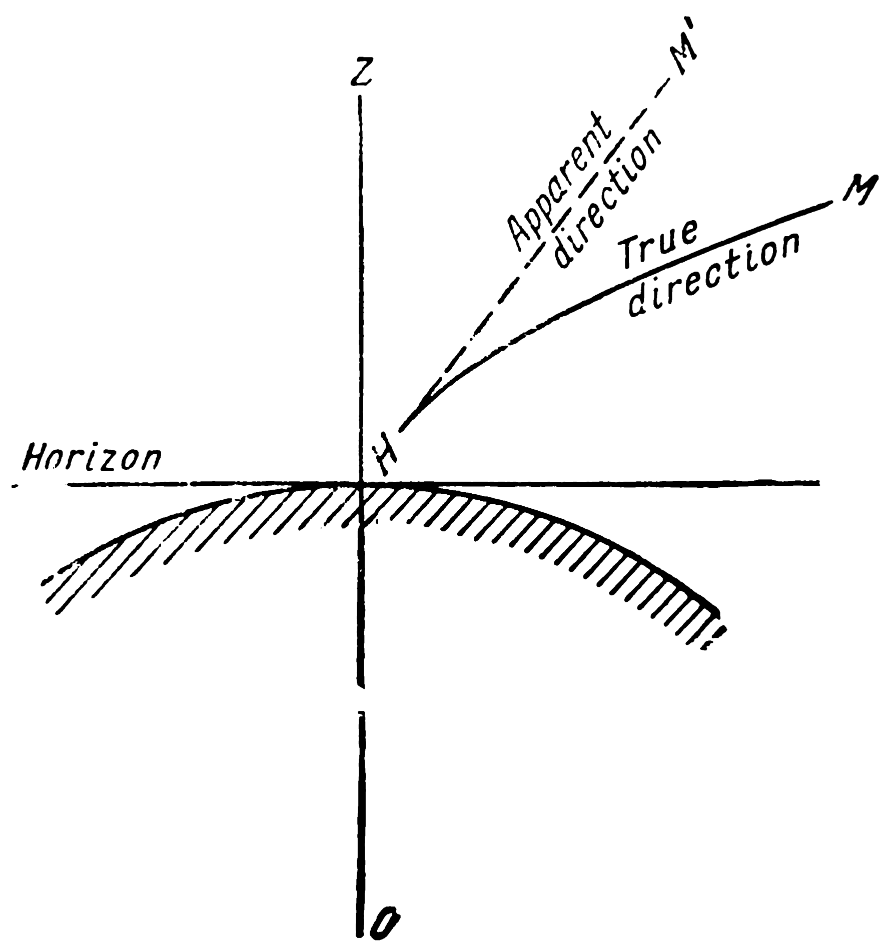


Fig. 10. Zenith attraction of meteors

meteors and fireballs they reach hundreds and even thousands of kilometres.

Meteors glow over a very short visible portion of their trajectories in the terrestrial atmosphere, a distance of several tens of kilometres which they cover in tenths of a second (more rarely, in a few seconds). On this portion of its trajectory the meteor experiences the earth's gravitational pull and deceleration in the atmosphere. As the meteor approaches the earth, its initial speed increases due to the latter's gravitational action, and its path is curved so that its observed radiant is displaced towards the zenith (the zenith is the point directly above the observer). For this reason, the action of the earth's attrac-

tion on meteoric bodies is known as zenith attraction (Fig. 10).

The slower the meteor the greater is the influence of zenith attraction, as may be seen from the following table, where V_g denotes the initial geocentric velocity, V'_g the same velocity distorted by the earth's attraction, and Δ_z the maximum value of zenith attraction:

V_g	10	20	30	40	50	60	70	km./sec.
V'_g	15.0	22.9	32.0	41.5	51.2	61.0	70.9	km./sec.
Δ_z	23°	8°	4°	2°	1°	$<1°$		

As a meteor plunges into the earth's atmosphere it is, in addition, decelerated. The deceleration at first is scarcely perceptible but becomes very considerable at the end of the path. According to the photographic observations of Soviet and Czech workers, deceleration on the final portion of the trajectory can reach 30 to 100 km./sec.^{2}, whereas it varies from 0 to 10 km./sec.^{2} over the greater part of the pathway. Slow meteors experience the greatest relative loss of velocity in the atmosphere.

The apparent geocentric velocity of a meteor, as distorted by zenith attraction and deceleration, is corrected accordingly to take account of these factors. For a long time, meteor velocities were not known with sufficient accuracy because they were determined from highly inaccurate visual observations.

The rotating-shutter photographic technique yields the most accurate determinations of meteor velocities. Nearly all determinations of meteor velocities obtained photographically in the U.S.S.R., Czechoslovakia and the U.S.A. show that meteoroids should be moving around the sun in closed elliptical orbits. Thus, it turns out that the greater part (if not all) of the meteoric matter belongs to the solar system. This result is in excellent agreement with the data of radar determinations, though the photographic results refer, on the whole, to the brighter meteors, that is, to larger-size meteoric bodies. The

distribution curve of meteor velocities, found by means of radar observations (Fig. 11), shows that the geocentric velocities of meteors lie principally within the range from 15 to 70 km./sec. (a certain number of velocity determinations that exceed 70 km./sec. is due to inevitable observa-

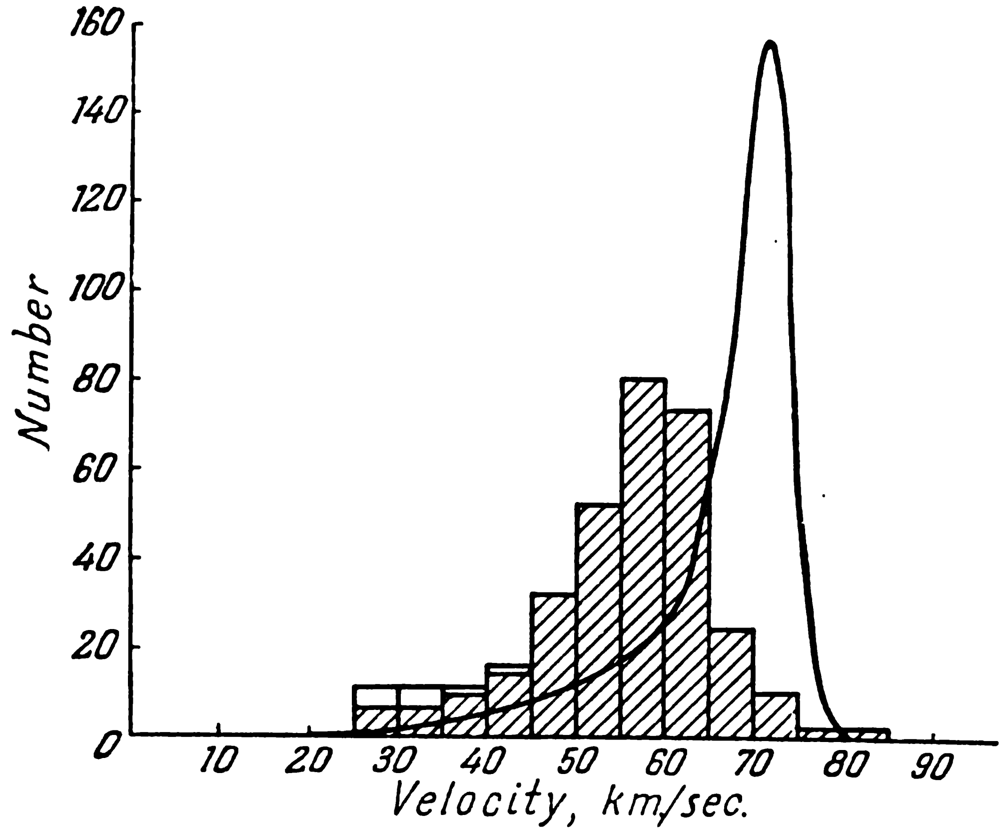


Fig. 11. Velocity distribution of meteors according to radar observations. The smooth curve gives the distribution that should be in the case of parabolic meteor velocities. The rectangles are observed elliptical velocities

tional errors). This is added support to the conclusion that meteors move around the sun in elliptical orbits.

The fact of the matter is that the earth moves in its orbit at a speed of 30 km./sec. so that head-on meteors moving at a geocentric velocity of 70 km./sec. are in motion about the sun at a velocity of 40 km./sec. But at the earth's distance, the parabolic velocity (that is, the velocity required to carry a body out of the solar system in a parabolic curve) is 42 km./sec. Hence, no meteoric velocity exceeds the parabolic velocity and, consequently, their orbits are closed ellipses.

The kinetic energy of a meteoroid plunging into the atmosphere with a high initial velocity is very great. Collisions between the atoms and molecules of the meteor and the air produce intensive ionization of gases in a large volume of space around the body. The numerous particles torn off the meteor form a brightly glowing envelope of incandescent vapour. The glow of this vapour resembles that of an electric arc. The atmosphere at meteor heights is highly rarefied and so the process of recombination of detached electrons and ions continues quite some time causing the column of ionized gas to glow for several seconds and, at times, even for a few minutes. Such is the nature of the self-luminous ionization trails which may often be observed in the sky after the meteor has passed. The spectrum of a luminous trail consists of the same elements as the spectrum of the meteor itself, only the elements are neutral and not ionized. Besides, the atmospheric gases also luminesce in trails. This is indicated by the lines of oxygen and nitrogen discovered in 1952-53 in the spectra of a meteor trail.

From meteoric spectra it will be seen that the meteoric particles consist either of iron (with a density exceeding 8 gr./cm.^{3}) or are stony with densities that should range from 2 to 4 gr./cm.^{3} The brightness and spectra of meteors permit an evaluation of their size and mass. The apparent radius of the luminous envelope of meteors of first to third magnitude is estimated at roughly 1 to 10 cm. However, the radius of the luminous envelope (determined by the spread of luminous particles) is far greater than the radius of the meteor itself. Bodies that dash into the atmosphere at 40 to 50 km./sec. and produce meteors of zero magnitude have radii of the order of 3 mm. and masses of the order of one gramme. The brightness of a meteor is proportional to its mass, in other words, the mass of a meteor of one magnitude is 2.5 times that of the next. And what is more, the brightness of a meteor is proportional to the cube of its velocity relative to the earth.

Meteoric particles plunge into the earth's atmosphere with a high initial velocity, and at heights of 80 and more kilometres they encounter a highly rarefied gaseous medium. The air density here is less than that at the earth's surface by a factor of one hundred million. In this zone, the interaction of the meteoric body and the atmosphere consists in bombardment of the body by individual molecules and atoms. These are molecules and atoms of oxygen and nitrogen, since the chemical composition of the atmosphere in the meteor zone is approximately the same as at sea level. In elastic collisions, the atoms and molecules of atmospheric gases either bounce off or penetrate into the crystal lattice of the body, which rapidly heats up, melts and vaporizes. The evaporation rate of the particles is small at first, then rises to a maximum and again diminishes towards the end of the apparent path of the meteor. The evaporating atoms leave the meteor at speeds of several kilometres per second and, since they have high energies, experience frequent collisions with air atoms, which produces heating and ionization. The incandescent cloud of evaporated atoms forms a luminous envelope around the meteor. Some of the atoms lose their outer electrons in collisions, with the resulting formation around the path of the meteor of a column of ionized gas that consists of a large number of free electrons and positive ions. The quantity of electrons in the ionized trail comes to 10^{10}-10^{12} per centimetre of path. The initial kinetic energy is expended on heat, light and ionization in roughly the ratio 10^6: 10^4: 1.

The deeper a meteor penetrates into the atmosphere the denser becomes its incandescent envelope. Like a flying projectile, a meteor produces a head shock-wave which accompanies the meteor into the lower levels of the atmosphere causing sound phenomena below 55 km.

The trail that a meteor leaves in its wake can be observed visually and by radar. The ionization trails of meteors are very easily seen in fast binoculars or in fast telescopes (so-called comet-seekers).

Fig. 12. The dust trail of a fireball (September 24, 1948); Top—photograph by N. Pavlov. Bottom—drawing by A. Yusupov; *I*—the trail left after the flight of the fireball, *II*—several minutes later (*IIa* and *IIb* correspond to parts of trail with different brightnesses)

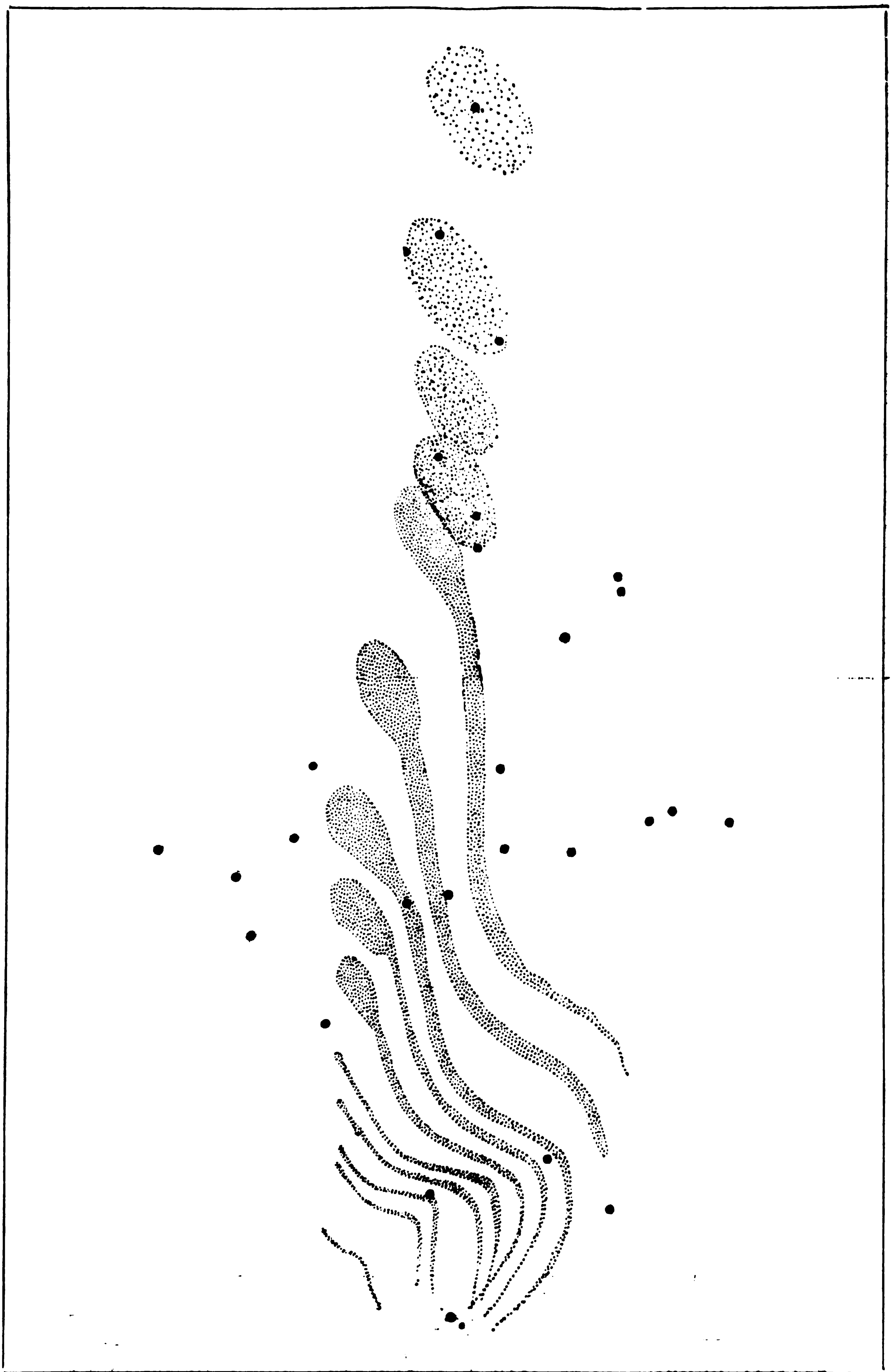


Fig. 13. The drift of the trail of a fireball (October 11, 1948) (after Fesenkov). The black dots are stars

On the contrary, the trails left by fireballs that penetrate to the lower and denser layers of the atmosphere consist chiefly of dust particles and are therefore seen as dark smoke clouds on the background of the blue sky. If such a dust trail is illuminated by the rays of the sun from below the horizon or the moon it is seen as silver strips on the background of the night sky (Fig. 12). Such trails are visible for hours at a time until dispersed by air currents. Now the trails of fainter meteors produced at 75 km. and higher contain only a small portion of dust particles and are seen exclusively because of the self-luminous atoms of the ionized gas. The duration of naked-eye visibility of an ionized trail is an average of 120 sec. for fireballs of the minus sixth magnitude, and 0.1 sec. for meteors of the second magnitude, whereas the radio-echo duration for these same bodies (given a geocentric velocity of 60 km./sec.) is 1,000 and 0.5 sec. respectively. Ionization trails deteriorate partly due to the recombination of free electrons and oxygen molecules (O_2) present in the upper layers of the atmosphere.

Like dust trails, ionization trails are affected by high-altitude winds that destroy them and disperse the remains until nothing is left (Fig. 13).

4. METEORS IN THE STUDY OF THE UPPER ATMOSPHERE

One of the first studies of the physical properties of the upper atmosphere was made by Lindemann and Dobson (England) in 1923. Despite their crude physical theory of meteors and Denning's imperfect visual observations, which were utilized by the authors, the latter succeeded in obtaining the first approximate data on the upper layers of the atmosphere. For one thing, they established the presence of layers of warm air at heights close to 80 km.

Meteor research methods of the upper atmosphere are

based on the following principles. The degree of meteor deceleration is proportional to the air density at the given height and to the square of the meteor velocity. Besides, deceleration depends on the mass of the meteor. Knowing the brightness, velocity and deceleration of a meteor in the atmosphere, it is possible to determine the mass, rate of evaporation and air density over its entire path.

If we take the molecular composition of the air to be the same in the meteor zone as at sea level, it is also possible to calculate the temperature of the air.

Photographic observations of meteors have yielded the following values for density (ρ), pressure (p), and temperature (T) of the atmosphere:

H (km.) . .	50	60	70	80	90	100	110	120
$\lg \rho$ . . .	—6.0	—6.5	—7.1	—7.3	—8.1	—8.6	—9.0	—9.4
p (mm.) . .	0.8	0.2	0.05	0.01	0.002	0.0006	0.0002	0.0001
T (deg.C.)	+80°	+80°	+10°	—50°	—30°	—10°	0°	+10°

The uneven variation of density with height is due to the variation of temperature in the upper atmosphere by layer. At a height of close to 80 km. the temperature of the stratosphere falls to approximately minus 50°C. This temperature minimum produces its effect on a large number of phenomena which occur at this height or for which 80 km. is the boundary. Observations show that at a height of 80-82 km. there is a change in the directions of winds in the stratosphere. At 82-83 km. there appear silverish or noctilucent clouds that apparently consist of ice crystals. These tiny crystals probably condense around microscopic particles of meteoric dust which remain after evaporation of meteors in this zone and which slowly settle downwards. The 82-km. height is the lower boundary of the aurorae, and also of an ionized layer, called the E-layer, that extends up to about 100 km.

Above the cooled layer of air at 80 km. the temperature of the stratosphere begins to rise reaching plus 10°C. at 120 km. This temperature rise in the highly tenuous upper

atmosphere is due to an increase in the mean velocity of molecular motion in the layers of the atmosphere up to 400 km. height. To understand better the physical conditions that exist in these "warm" layers of the upper atmosphere we must take note of the fact that the temperature of these layers expresses nothing other than the mean velocity of random thermal motion of a relatively small number of molecules and atoms. A thermometer or any other body raised to a height of over 100 km. will have a different temperature, much lower than that of the atmosphere, depending on the absorbing properties of its surface and the conditions of illumination by the sun. In a highly rarefied medium, heat exchange has but slight effect on the temperature of a body.

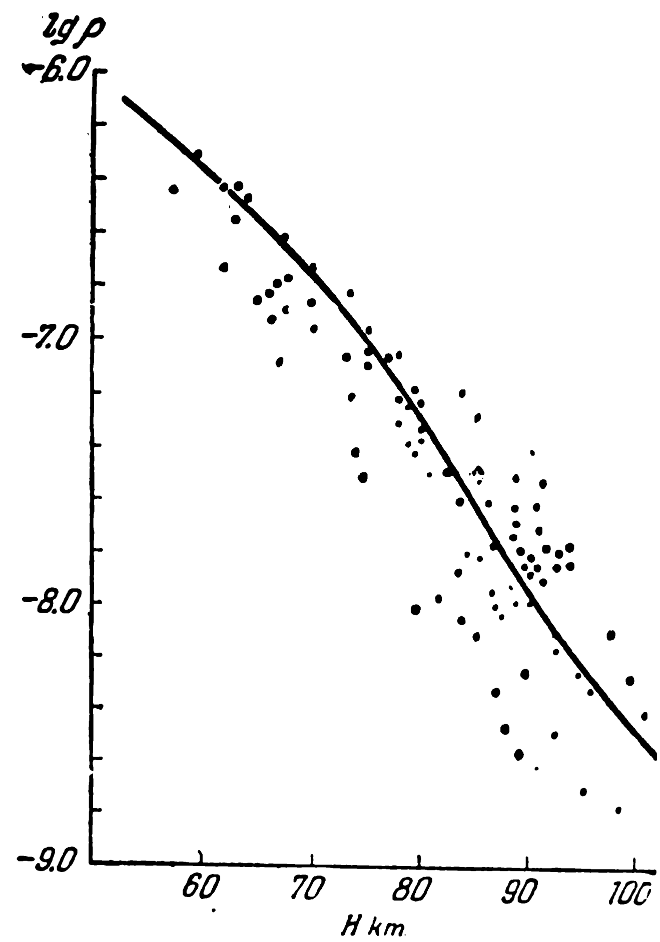


Fig. 14. The air density (ρ) in the upper layers of the atmosphere. The dots are determinations made from meteor data, while the solid line is the standard density curve of the atmosphere. Plotted on the vertical scale are logarithms of the density

Direct measurements conducted in 1947 and later with automatic instruments in rockets have generally confirmed our data (obtained from meteor observations) concerning the physical properties of the upper layers of the atmosphere, in particular the temperature rise in these layers of the air.

However, these same direct measurements have made it possible to establish certain discrepancies in results obtained from meteor data. Such discrepancies are due to the specific loose structure of some meteors. It may be that there are icy meteoric bodies in which frozen water

and even ammonia compounds surround minute iron or stone particles. Such icy or loose meteorites have a low specific weight and act very much like a "sail" in flight through the atmosphere because of their relatively large cross section and small weight.

The information on the upper layers of the atmosphere obtained from meteor photographs give only a general picture of the properties of these layers for about 40° north latitude (U.S.S.R., U.S.A.) and leave unanswered many questions that have to do with the physical state of these strata. How does the state of the upper atmosphere vary with latitude? How do its properties vary seasonally and diurnally at different latitudes? What effect do lunar and solar tides have on the earth's atmosphere? To answer these queries it is necessary to accumulate extensive experimental material and make a more precise and detailed study of the structure of the upper atmosphere. This is now being done on a grand scale by artificial earth satellites.

Radar, supported by certain fundamental data obtained from meteor photographs, affords a most promising method for the further study of the upper layers of the atmosphere. But artificial earth satellites will probably say the last word in this field.

The English meteor investigator T. Kaiser published, in 1953, a paper in which he showed the great possibilities of radar observations of meteors in studying the physical properties of the upper atmosphere. Radar observations make possible a determination of the dependence of height of appearance of meteor trails on the geocentric velocity of the meteor. A relationship of this type permits us to find the density and pressure of the atmosphere in the meteor zone.

The average meteor height (H) observed by radar is related to the geocentric velocity (V_g) as follows:

V_g	20	30	40	50	60 km./sec.
H	87.5	90.9	94.8	98.3	101.5 km.

Atmospheric pressure determined from this information comes out at 0.0007 mm. of mercury at a height of 97 km. The temperature calculated on the assumption that the molecular composition of the atmosphere in the meteor zone is the same as at sea level rises from minus 75°C. at 88 km. to minus 30°C. at 100 km. The density falls from 10^{-8} gr./cm³. at 87 km. to 10^{-9} gr./cm³. at 101 km. A comparison of the logarithms of atmospheric density obtained by radar and photographic studies of meteors and also on the basis of direct measurements during rocket flights is given in the following table:

Height	90	95	100 km.
a) Radar observations	—8.25	—8.6	—9.0
b) Photographic method	—8.1	—8.4	—8.6
c) Rocket data	—8.4	—8.7	—9.1

Site of observation:

a) Jodrell Bank (England)	$\varphi=53°$,
b) Massachusetts (U.S.A.)	$\varphi=42°$,
c) New Mexico (U.S.A.)	$\varphi=32°$.

The values of air density obtained from radar observations are in close agreement with direct rocket measurements. The unquestionable advantage of radar techniques in studying the upper layers of the atmosphere from meteor data is the speed with which they are obtained, to say nothing of the possibility of conducting observations in the day-time and in foul weather. To obtain 200-300 observations of meteor heights and velocities necessary in making a reliable calculation of the pressure, about 10 days of continuous radar observations is required, whereas the photographic method requires much more time and labour, and the launching of a stratosphere rocket or a satellite is a very complex and expensive undertaking.

The next problem is the determination of speed and direction of air currents, that is, of high-altitude strato-

sphere winds. The direction and speed of stratosphere winds are successfully ascertained from observations of the drift of meteor trails which are carried along by the air currents like floats in water. From statistical data on the drift of trails collected by the author, it may be seen that at heights below 82-83 km. the predominant direction is westwards, while higher it is eastwards with a velocity of the order of 50 m./sec. (Fig. 15.) Similar data

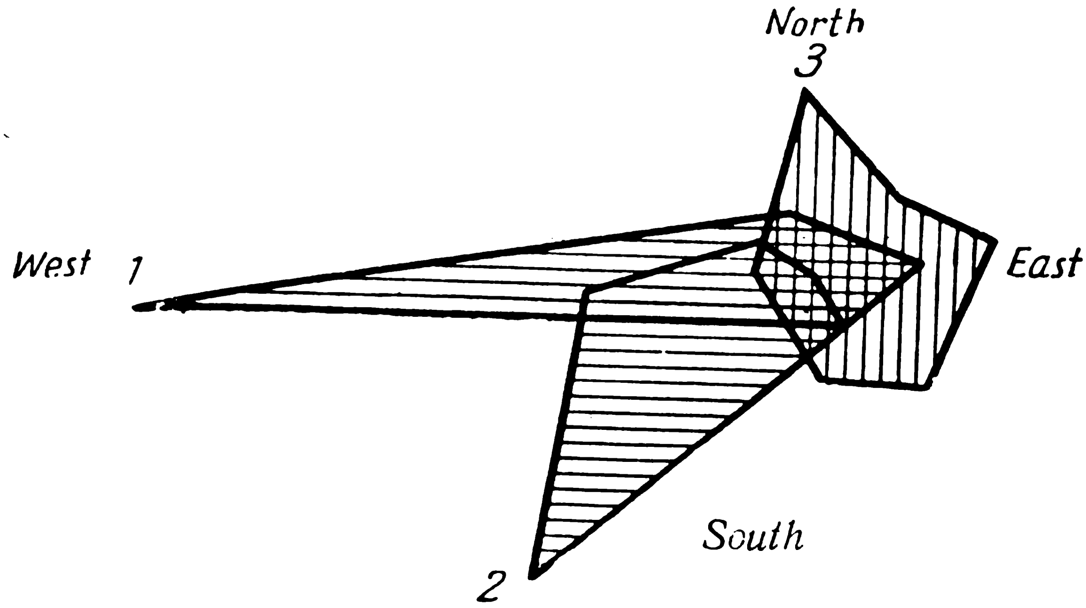


Fig. 15. Air currents in the upper atmosphere of the northern hemisphere of the earth (temperate belt) : *1*—from day-time meteor trails; *2*—from noctilucent clouds; *3*—from luminous night-time meteor trails (*1* and *2* are below 82 km., *3* is above 82 km.)

were obtained in Ashkhabad by Astapovich who as early as 1944 discovered variations in the direction of the wind at heights above 80 km. The variations were diurnal in clockwise rotation with the sun.

Radar observations of the drift of meteor trails were carried out in the autumn of 1953 at Jodrell Bank by Greenhow on a wavelength of about 8 m. This apparatus yielded every 24 hours over 3,000 usable radio-echo observations. The wind velocity was in excellent agreement with the Soviet visual determinations and, on the whole, was within 10 to 50 m./sec. The wind was found to rotate with the sun in a clockwise direction both with a semi-

diurnal and a diurnal period. This rotation had been earlier discovered in the U.S.S.R. on the basis of visual observations.

Observations in the southern hemisphere of the earth (Adelaide, Australia) have shown that here the upper layers of atmosphere move in the opposite direction, counterclockwise.

Special observations showed that, within several degrees, the winds in the upper layers of the atmosphere blow horizontally, and vertical currents of air may be ignored. Observations of meteor trails at different altitudes have shown that wind direction and velocity vary with altitude. Air-current speeds increase roughly 2.7 m./sec. per kilometre of altitude. At 75 km. height the average velocity of stratospheric wind is 10 m./sec., while at about 100 km. it is already 60 m./sec. Noted also are considerable fluctuations in the direction and intensity of the wind, which is an indication of complex and irregular air currents at high altitudes. All this signifies that the entire blanket of terrestrial atmosphere is in powerful and complex circulation. There is still a great deal of work to be done by meteor techniques at many points on the earth in the study of this circulation.

5. METEORS AND INTERPLANETARY TRAVEL

October 4, 1957 is the starting point of man's conquest of cosmic space. It was on this date that the Soviet Union launched into orbit the first artificial satellite of the earth. During the year that has elapsed since that remarkable day the U.S.S.R. and the U.S.A. have launched other satellites, the largest of which by far is Sputnik III—a veritable cosmic laboratory 3.6 metres long, 1.7 metres across and weighing over 1,300 kilogrammes. The time is not far off when manned rocket ships will be hurtling through interplanetary space. And we will have to know what this

meteor cloud is like that cosmic craft will encounter, how probable and how dangerous such encounters with meteors will be. The first scouts sent into outer space are the artificial earth satellites. Due to very high relative velocities meteors represent a definite hazard to rocket ships, for even the tiniest meteoric particles are capable of puncturing the skin of such a vehicle or of producing a lot of damage. The probability of a rocket ship encountering a random meteor is the greater the smaller the size of the meteor, because the number of small meteoric bodies is many-fold the number of large bodies.

The probable frequency of a rocket ship of area about 100 sq. m. encountering meteors of different mass and the thickness of a steel shield necessary to protect the ship from such meteoric impacts is given below:

Meteor, mass (gr.)	1	0.01	0.0007
Probable interval in hours between two successive collisions of rocket and meteors	14,000	140	9
Minimum thickness of steel shield for protection (mm.)	10	3	1

The above table was compiled on the basis of visual and radar observations and refers to relatively large-size meteoric particles. The very first rockets shot into the upper atmosphere of the earth, above the meteor zone, in the main corroborated these findings. But they also revealed the action, on the metallic skin of the rockets, of a still more numerous group of tiny meteoric dust particles of size from 0.1 to 10 microns. These were christened micrometeorites. The metallic surface of a rocket exhibits dents and gashes produced by the impacts of micrometeorites. This phenomenon is known as meteor erosion in analogy with the weathering of terrestrial rocks by water and air.

However, the nature of meteor erosion differs essentially from the simple mechanical destruction of rocks by water and air. Stanyukovich and the writer have shown that when a micrometeorite hits the metallic skin of a rocket with cosmic velocity the result is a real miniature explosion. The effect produced by micrometeorites on the rocket shell depends on the kinetic energy of the particle, which is known to be proportional to its mass and the square of its velocity.

Problems of meteor erosion and the meteor hazard are now uppermost in the minds of men working in the new field of astronautics, or, as the founder of this science, Tsiolkovsky, called it, astrogation. No wonder then that one of the principal scientific objectives of the first artificial earth satellites was the study of micrometeorites, their number and kinetic energy.

To register the impacts of micrometeorites, meteorological rockets sent up above the meteor zone (that is, upwards of 100 km. above the earth's surface) and artificial satellites are being equipped with special sensing devices, which consist of piezocrystal cells that produce electric pulses when micrometeorites strike the rocket casing. The pulses are amplified and as special radio signals are relayed to earth. A record is made of the number of impacts experienced by the sensing device of the satellite in encounters with micrometeorites. A sounding of meteor space, taken by a Soviet geophysical rocket on February 21, 1958, showed that the greatest number of dust particles was encountered by the rocket at an altitude of 125-250 km. with 44 impacts registered, while at heights exceeding 300 km. only nine encounters were recorded. The upper layers of the atmosphere apparently have a certain quantity of meteoric particles—the remnants of disintegrated meteors—which have been decelerated by air resistance and are slowly settling down to earth much like solid particles do in turbid water.

One is struck by the big discrepancies in Soviet and American estimates of the number of micrometeorites. T. Nazarova, of the Institute of Applied Geophysics, U.S.S.R. Academy of Sciences, reckons the number of micrometeorite impacts per square metre of satellite surface per second in tens, while American data suggests units or even fractions thereof. There is a rather large spread in the American findings too: from 0.04 to 1.7 impacts per square metre per second (or from 157 to 6,150 impacts per hour on the same area). Different apparatus and measuring techniques as well as variations in the density of the meteor medium through which the earth moves are sufficient explanation for such divergence in the first results of micrometeorite counts by means of artificial satellites. Further careful and long-term observations are needed in order to obtain reliable statistic data.

Artificial earth satellites do not only register collisions with micrometeorites, they are in themselves probes that live for long periods of time outside the earth's atmosphere in meteor space and experience intensive meteoric bombardment. During the many months that the first Soviet and American earth satellites were "Baby Moons" circling our planet every one and a half hours, not a single one of them was seriously damaged or deflected from its orbit by the impact of a large meteoric body. Yet, during this time the earth passed through relatively dense meteor streams. The foregoing strongly suggests that the meteor hazard may not be so menacing as appears from initial estimates and that it will not be a deterrent to projected man-carrying expeditions into cosmic space.

Special shielding will probably have to be used to protect rocket ships from meteor impacts. And during periods of big meteor showers, rocket missions will probably be cancelled much as routine air schedules are called off when the weather is bad in the troposphere. Still

other ways may in future be found to protect rocket craft from encounters with large-sized meteors.

In conclusion we have yet to mention another use of artificial earth satellites as probes for space flights not in their passage through the meteor medium—but in their fall back to earth. We know that the tenuous layers of air that extend up to roughly 1,000 kilometres above the earth's surface gradually retard the motion of artificial satellites forcing them, ultimately, to spiral into the planet. The time comes when the satellite has dropped to layers of the atmosphere that produce meteoric phenomena and which may be called the meteor zone. Here, the satellite itself becomes something in the nature of a huge meteorite getting incandescent as it interacts with the dense air; it begins to glow and disintegrates like a slow fireball. For a very short time, the earth satellite is an enormous artificial meteor. Unlike ordinary meteors, this one has a mass, shape, composition and initial velocity that are well known, and by observing it glow and disintegrate in the meteor zone one can put the fundamental principles of the physical theory of meteors to an experimental test. Since everything happens very quickly it is no easy matter to observe an artificial meteor, but present-day radar techniques and a broad network of visual observers in the artificial satellite programme make such observations possible.

By way of illustration, take the first Soviet satellite, Sputnik I. It began to disintegrate January 3, 1958 when it split into two pieces and then into eight. Sputnik II was seen to glow and disintegrate on April 14, 1958 over the Lesser Antilles, Brazil and the Atlantic Ocean. Observations of this nature have only just begun, but they are already adding to our knowledge about meteors. Thus it is that the artificial earth satellites supply science with valuable material even in their death throes.

6. COLLISIONS OF METEOROIDS WITH THE EARTH

Big meteors penetrate deep into the earth's atmosphere and sometimes fall to the ground. The movement of such bodies in the lower layers of the atmosphere and phenomena that accompany the dropping of meteorites present a number of characteristic peculiarities.

The compressed air in front of a rapidly moving meteor causes a shock wave, on the surface of which the pressure varies in jumps. As the compression area moves to either side it forms a head wave which resembles that ordinarily produced by a ship moving in water. In the conical space defined by the head wave there appears a wave of rarefaction and turbulence. Energy loss due to the formation of the shock and head waves and also in eddy movements of the air which accompany these waves causes rapid deceleration of the meteor in the lower levels of the atmosphere.

In the upper atmosphere, deceleration along the trajectory is quite insignificant, and only at the end of the path does the loss of speed attain a perceptible magnitude. But below 60 km. the meteor experiences progressively greater deceleration and at an altitude of 20-25 km., in the so-called delay region, the meteor usually loses all its initial cosmic velocity. Fireballs are sharply decelerated, and meteorite fragments dropped from the delay region reach the earth under the force of gravity at a moderate speed of 100-200 m./sec. due to the slowing-down action of the dense air.

The head air wave of a fireball and also the fluctuations in air density in the rear part of the meteoric body produce a series of sounds—the crack of cannon fire and the clap and roll of thunder—which greatly impress anyone who sees a fireball in flight. Below is a description of a person who saw a brilliant detonating fireball on April 23, 1929.

"On the night of the 22nd of April, 1929, two friends of mine and I went out hunting. Zilair (a village in Bashkiria) was buried in a darkness just faintly illuminated by the murky light of the moon. The pine forest was complete silence. Suddenly the whole area was floodlighted as if from an enormous electric light. At that moment we were on a rather high rocky hill. We stopped dumbfound. In this light the gloomy pine-trees became green, every stone and every stream running down the slope was visible. It was like a huge flood-light cutting a broad shaft through the dark. A dazzlingly brilliant greenish ball of fire passed across the sky to the north of Zilair shooting out sparks and leaving behind a glowing trail that gradually dissipated. Then everything vanished and again darkness enveloped the earth. The time was 15 minutes past midnight. A minute and a half or two later there was a sharp clap of thunder with an echo-like crack, which coincided with a slight tremor of the ground. The sound was something like a distant report of a gun."

The Khmelyovka meteorite that fell March 1, 1929, in the Tara District of the Omsk Region may be used to illustrate the distance at which the sounds of a fireball are audible. Sounds were recorded within a radius of 125 km. as the map in Fig. 16 shows. And beyond the dead belt of radius 200 km. sounds were again heard due to refraction of the sound waves in the upper layers of the atmosphere.

Powerful sound phenomena were also noted during the falls of the giant Sikhote-Alin and Tunguska meteorites.

In the lower part of its trajectory a fireball glows with a different light. The glowing meteor envelope that consists of incandescent vapour grows considerably in size. The fireball appears to the observer as a brilliantly glowing dew drop or pear-shaped body because the re-

sistance of the air medium streamlines the front part. A determination of the angular diameter of the head of a fireball shows that its linear dimensions reach several hundreds of metres. Although in visual estimations op-

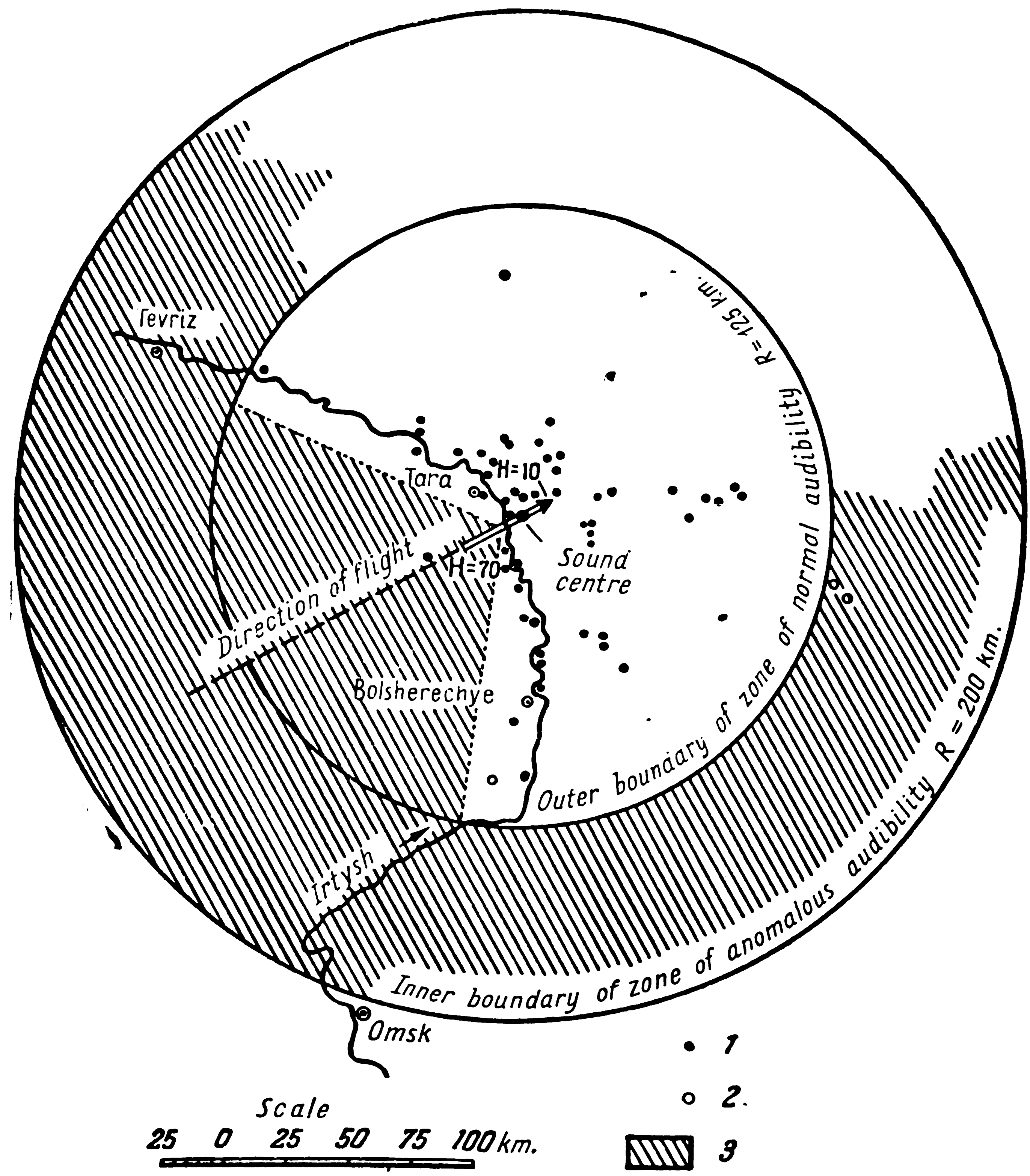


Fig. 16. Distribution of sound audibility during the flight of the Khmelyovka meteorite of March 1, 1929. *1*—points that registered sound phenomena, *2*—points where no sounds were recorded, *3*—dead belt (absence of any sound phenomena)

tical illusions inevitably play a role, with the result that the fireball appears to the observer greater than its true angular size, it is obvious that the diameter of the incandescent envelope ("cap") of the fireball is tens of times greater than the diameter of the meteoric body itself.

The light of the fireball envelope in the lower layers of the atmosphere is quite different from that in the meteor zone. The increasing density of the atmosphere and the mounting quantity of incandescent vapour of meteoric matter in the envelope of the fireball make for a sudden rise in the role of thermal light. This results in the lower part of the trajectory of a fireball often having a yellowish or reddish tinge. Sometimes the colour of a fireball is found to change from bluish or greenish in the upper part of the trajectory to a red hue in the lower regions of the atmosphere. In most cases the head of a fireball appears a dazzling white like a bright electric lamp, whereas the tail, which consists of rapidly cooling vapours and splashes of meteoric matter, has a reddish hue.

Due to the high temperature of the shock wave of compressed air that reaches a temperature of several thousand degrees, the surface of the body melts, boils and evaporates. The nature of these phenomena was recently studied by the Soviet meteorite researcher E. Krinov on a large number of fragments of the iron Sikhote-Alin meteorite. Boiling iron was swept by the current of air from the front part of the meteorite to the rear part. The fusion crust of the meteorite is covered with fine jets of iron and, in places, tiny drops of boiling metal that have solidified (Fig. 17). An interesting thing is that all such iron droplets are hollow inside, which indicates that the iron was boiling very intensively. The front part of the body is constantly being smoothed and polished by the air stream, and the angular shapes of the original meteoric body become characteristically streamlined.

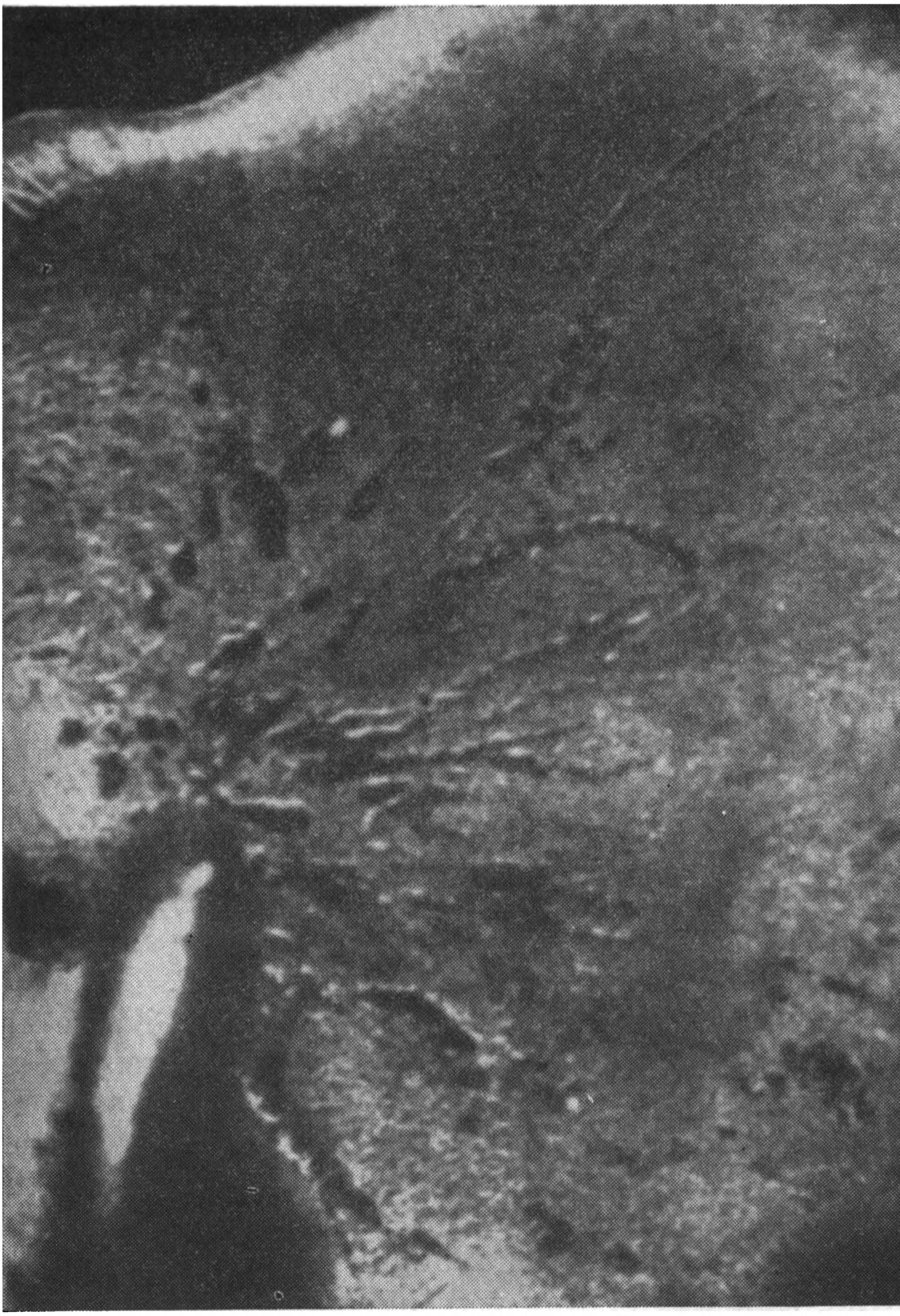


Fig. 17. Fusion crust of Sikhote-Alin meteorite with solidified splashes of nickel-iron

The material which abundantly evaporates from the surface of the meteor is swept back into the tail of the fireball in a pulverized state; here it cools and condenses into minute dust particles, some of which have dimensions of the order of microns, the result being that the dust trails of fireballs hang in the air for hours at a time and settle down very slowly. For instance, the trail of the Sikhote-Alin meteorite was visible for several hours right up to sunset.

The dust trail gradually disperses, but by far not so rapidly as the gaseous trails in the upper regions of the atmosphere. The wind blows at different heights with different speeds and in different directions and so twists the original straight dust trail of a fireball into rings and zigzags. The fanciful trails of three brilliant fireballs may be seen in photographs obtained by the noted Russian traveller Kozlov (the Alashan fireball of December 12, 1905), by the TASS correspondent Debabov (the Chukotka fireball of October 19, 1941), and by the *Penza Pravda* newspaper reporter Pavlov in the village of Danilovo, Penza Region (the trail of this fireball of September 24, 1948, is shown in Fig. 12).

During the first few moments after the flight of a fireball its dust trail is straight; observers directly under it at this time see it as a dark vertical column which is sometimes erroneously taken for the aftermath of an explosion of the meteorite.

The drift of fireball dust trails indicates that the winds blow in different directions in the regions of the atmosphere between 20 and 70 km.; the wind velocity here is much lower than in the upper layers (the meteor zone) and, as a rule, does not exceed 10-15 m./sec.

The dust trails of fireballs make it possible to assess the intensity of pulverization of large meteoric bodies in the atmosphere. This process is most intensive in the lower regions of the upper atmosphere, and ordinarily only a small part of the matter of the meteor reaches

the earth. To take an example, in the estimation of Academician Fesenkov, only one per cent of the initial mass of the Sikhote-Alin iron meteorite reached the earth; the remaining material of the meteorite was converted into fine dust which slowly settled down through the atmosphere. According to Krinov, the minute iron droplets that were swept from the surface of the Sikhote-Alin meteorite had a density not of 8 gr./cm.^{3}, but much less, but even if we take the density of the pulverized material to be a tenth of that figure, we will find that the final mass of the fallen meteorite was only a small fraction of the initial mass of the body. In the case of the fireball of September 24, 1948, its entire original mass, estimated on the basis of brilliance as 250 kg., was completely pulverized in the atmosphere and was observed for over half an hour as a bright trail in the light of the sun which had just set.

Numerous air eddies that form over the whole surface of the meteoric body drill into it characteristic depressions called regmaglyptes. Regmaglyptes are formed during the final stage of flight of the body in the atmosphere when the velocity is considerably reduced, the shock wave has weakened or vanished and the body itself is breaking up into pieces. This follows from the fact that the dimensions of the regmaglyptes are the greater, the greater the size of the fragment. Here we thus have a very interesting phenomenon of air eddies that stream past the separate fragments.

Aside from intensive evaporation and pulverization of material from the surface, large meteoric bodies of irregular form experience varying loads due to uneven stresses created by the air eddies. This uneven loading breaks the meteor into fragments. In many instances, separate pieces of meteorites found at the place of fall are complementary and join to form big chunks, as, for example, the two iron chunks of the Boguslavka meteorite found half a kilometre apart fitted into one piece. The

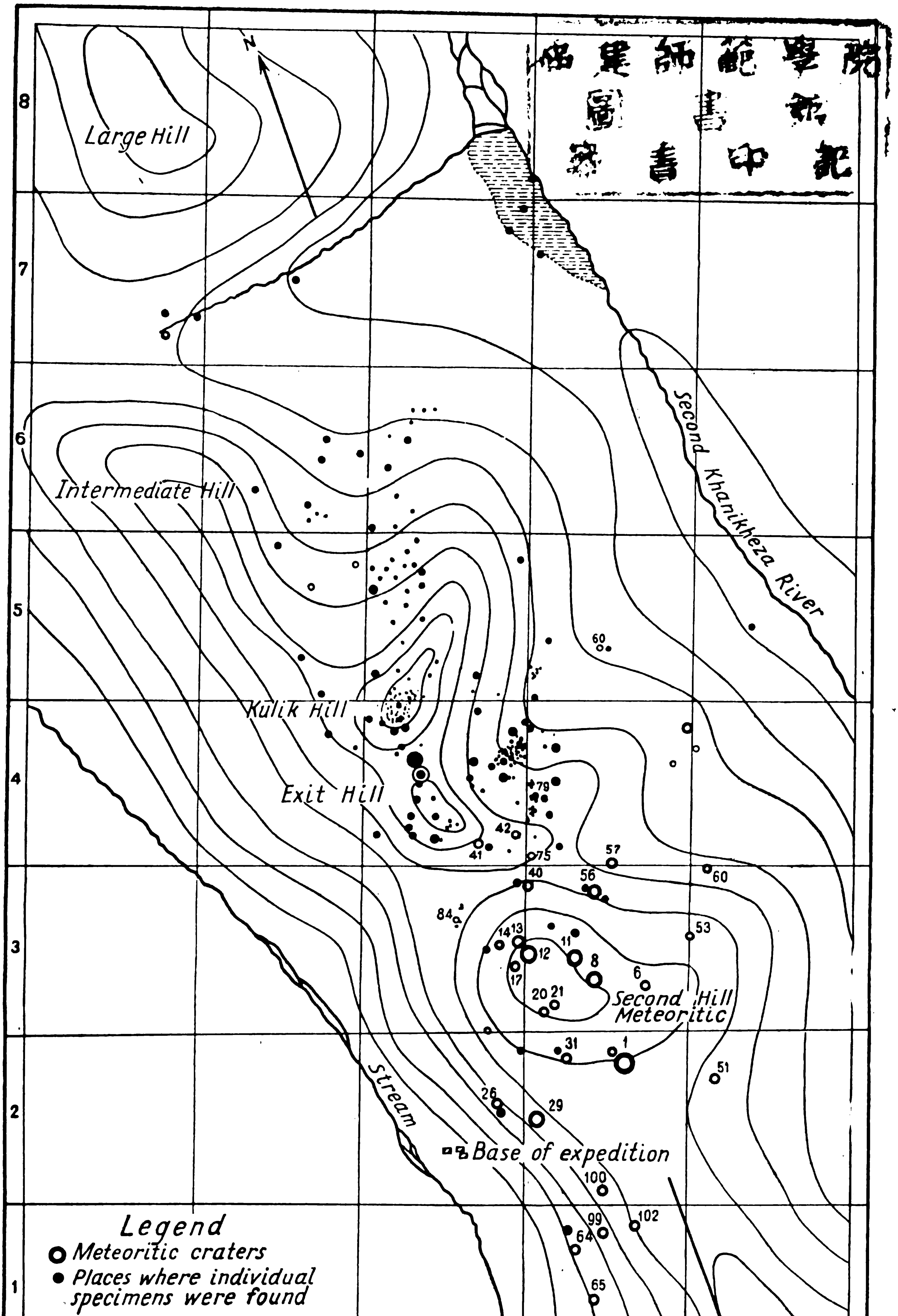


Fig. 18. Dispersion ellipse of fragments of the Sikhote-Alin meteorite

fragmentation of meteoric bodies in the air into tens, hundreds and even thousands of pieces is a common phenomenon, the result being a stony or iron shower that falls to earth from the delay region. The fragments spread out in all directions, like an artillery shell exploding in the air, and cover the area of a so-called dispersion ellipse. This was what happened in the case of the Sikhote-Alin meteorite of February 12, 1947, when several thousand iron fragments fell on an area the form of an ellipse with the major axis, directed from NNW to SSE, about 6 km., and the minor axis 2 km. (Fig. 18). The fragments of the iron Zhovtnevy Khutor meteorite, which fell October 9, 1938, covered a dispersion ellipse with a major axis of 11 km., orientated from north to south. The iron shower of the Kainsas meteorite of September 13, 1937, had a dispersion ellipse with axes of 40 and 7 km.

The higher the delay region of the meteorite and the larger the number of fragments, the greater the area of the dispersion ellipse. The smaller the angle of inclination of the meteorite trajectory to the horizon, that is, the more sloping its path, the more elongated will be the ellipse.

The fragments of a falling meteorite make rather deep depressions in the ground. Some of the fragments that have only a small kinetic energy rebound upon falling and remain lying on the surface of the earth. Meteorite fragments are covered with a characteristically blackish fusion crust which distinguishes them from terrestrial rocks. They fall cold because the whole passage of the meteorite through the atmosphere is accomplished so quickly that the melting and evaporation heat does not have time to penetrate into the body.

After their recovery, meteorites are put on display in museums and become the subject of scientific investigation. In the U.S.S.R., meteorite studies are conducted by the Meteorite Committee of the U.S.S.R. Academy of Sci-

ences now headed by its chairman Academician Fesenkov and scientific secretary Krinov. The branch of science that treats of meteorites is called meteoritics. During recent years it has made considerable progress and has now become an independent branch of science.

The dimensions of individual meteorites are extremely varied. Very characteristic in this respect is the Sikhote-Alin meteoritic shower in which the largest chunk had a mass of 1,745 kg., while the tiniest individual meteorites covered with a fusion crust and found on the leaves of trees weighed less than 0.2 gramme. The largest single iron meteorite (60 tons) was found in the Hoba West region of Africa. The largest stony meteorite, Long Island, weighs 564 kilogrammes. Meteoric dust collected on the tops of high snow-covered mountains, where the possibility of dust of terrestrial sources collecting is almost completely precluded, has yielded minute dust particles several microns in size and weighing a fraction of a milligramme. Such particles probably enter the earth's atmosphere at a very low geocentric velocity so that they do not even glow. Apparently, this is the result of the earth encountering clouds of interplanetary cosmic dust.

At first glance, the shapes of different meteorites appear to be quite irregular. However, Krinov, after a study of individual specimens of the Sikhote-Alin meteorite, has recently arrived at the conclusion that they are large-size crystals (octahedrites) or so-called nickel-iron "beams" in the form of highly fanciful concretions (druses) and polished by the air in the passage through the atmosphere. In the same way, the shapes of certain other meteorites may be explained as the result of air action on a body which originally had a regular geometric shape due to its crystalline structure. This fact is of great interest in the study of conditions that cause changes in the

shapes of meteorites during their passage through the atmosphere.

Meteorites have densities that range from 2.5 to 8.8 gr./cm.^{3} Recall that the density of the rocks of the earth's crust varies between 2.0 and 3.4 gr./cm.^{3}, and the mean density of the earth's crust is equal to 2.67 gr./cm.^{3} Only in the core of the earth, at depths exceeding 2,900 km. does the rock density rise to 11 gr./cm.^{3}, so that the density of iron meteorites may be compared only with the material that comprises the central core of the earth.

In composition, meteorites are divided into stony and iron types. The latter consist of iron and nickel, the nickel accounting for anywhere from 5 to 18 per cent. The nickel iron of meteorites forms peculiar crystals unknown on earth—large octahedrites. Polished sections of iron meteorites exhibit also a more or less dense network of lines that results from the crystallization of nickel, so-called Widmanstätten figures and Neumann lines (Fig. 19). The character of the crystallization of nickel iron in meteorites strongly suggests that iron meteorites formed under conditions of high temperature in the absence of any perceptible gravitational force. Such conditions might arise either deep within large planets or in small concentrations of incandescent matter at one time ejected from the sun at a high initial velocity and subjected to rapid cooling.

The chemical composition of stony meteorites resembles that of terrestrial rocks. Here we find oxygen comprising an average of 36 per cent of meteorites by weight, iron (26 per cent), silicon (18 per cent), magnesium (14 per cent), nickel, cobalt, copper, phosphorus, sulphur, carbon, calcium, sodium, potassium, aluminium, manganese, and chromium.

According to the data of Academician A. E. Fersman and other investigators, the chemical composition of meteorites and the earth is very similar (Fig. 20), which is a point in favour of a common origin for these bodies.

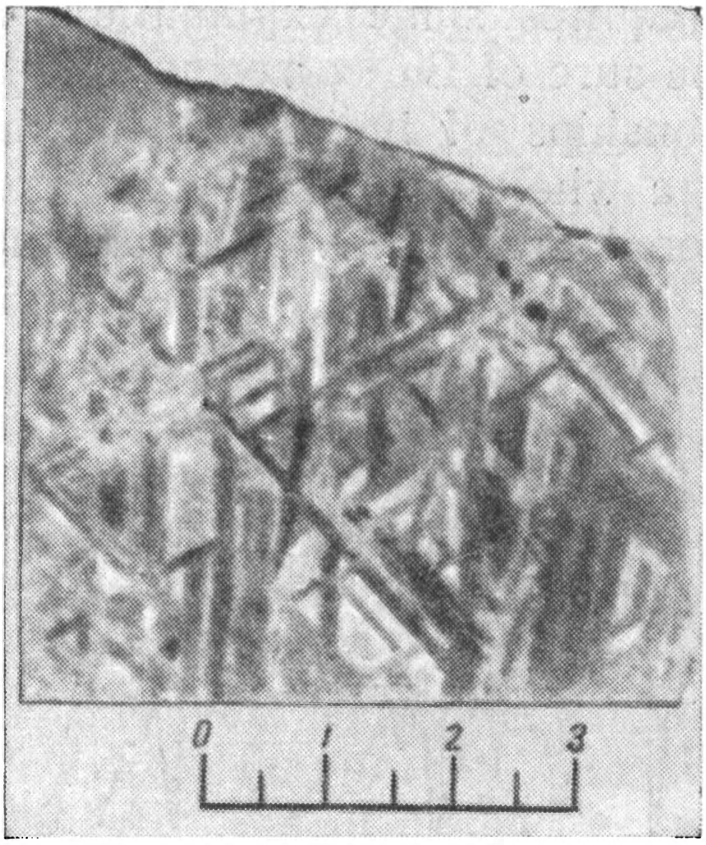
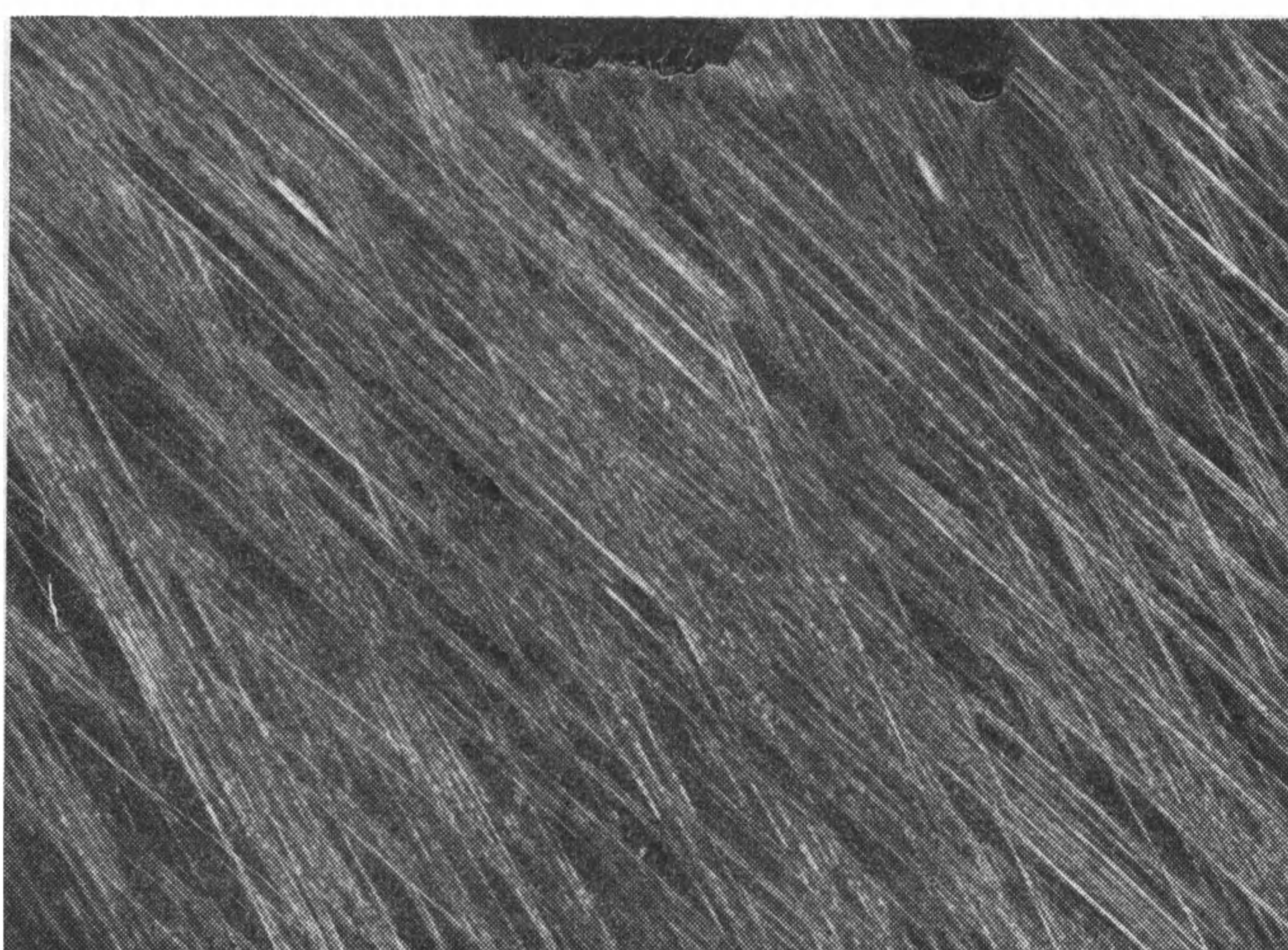


Fig. 19. Widmanstätten figures (top), and Neumann lines (bottom on polished and etched section of iron meteorite (the scale at the top is in centimetres)



This very important cosmogonic conclusion is a generally accepted opinion, but it requires some explanation. On the one hand, we cannot be sure of the correctness of the volume and weight relationships of individual chemical elements for the earth as a whole, for its average composition cannot be considered as definitively established.

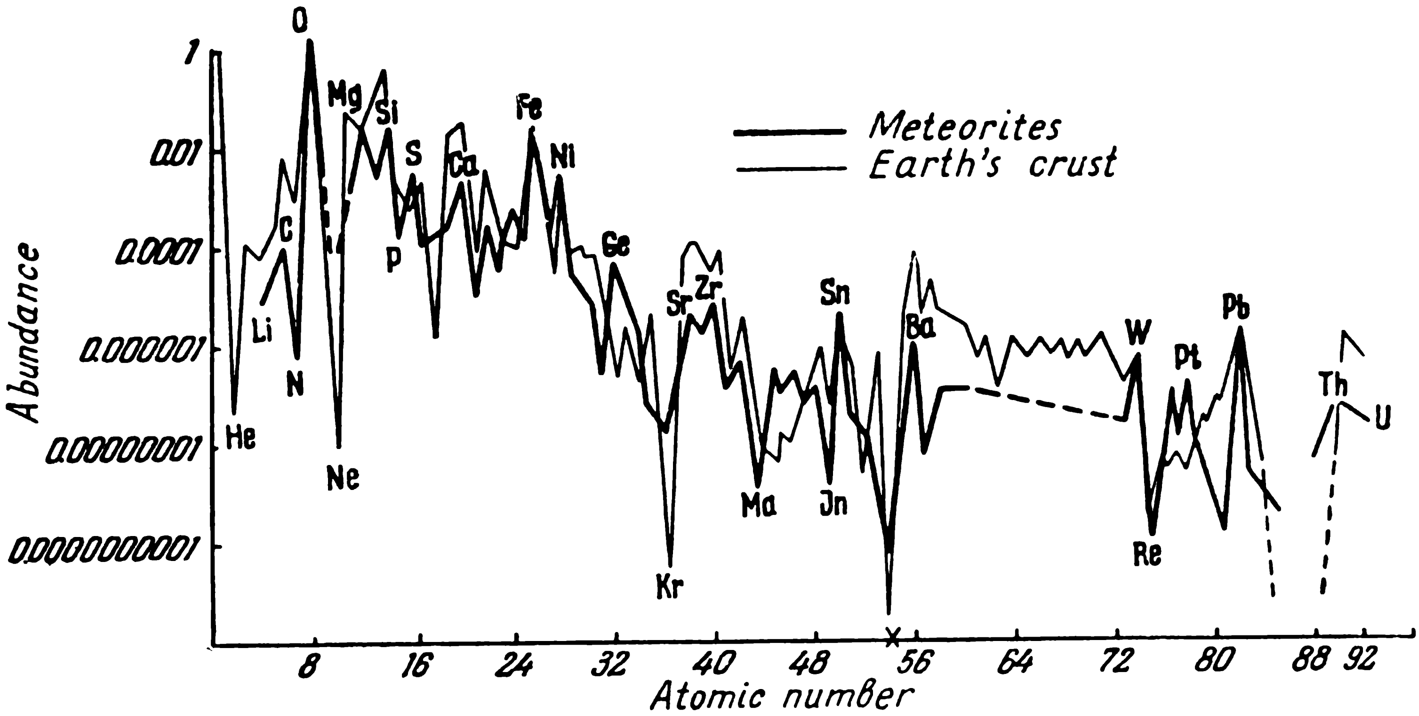


Fig. 20. Chemical composition of earth and meteorites (after A. Fersman)

For a long time it was thought by geophysicists and geochemists that the earth had an iron-nickel core suggestive of the composition of iron meteorites. However, Lodochnikov in the U.S.S.R. (1939) and later Ramsey in England (1948) pointed out that more likely the core of the earth consists of the same chemical elements as the crust, but that these elements had experienced, under the high pressures that exist deep within the earth, radical alterations of structure, destruction of the crystal lattice and a peculiar type of "packing" of atoms that results in a substantial increase in density.

On the other hand, the average chemical composition of meteorites is not at all reliably known, for the number of meteorites found and studied by chemists is not sufficiently representative of the entire mass of meteoritic

matter that may fall to earth. And what is more, the composition of meteoric bodies may vary with their distance from the sun. One of Academician Schmidt's closest associates, B. Levin, believes that meteoroids revolving about the sun in the outer cold regions of the solar system can in large measure consist of ices of ammonia and other similar compounds, whereas these compounds have completely evaporated from meteoroids closer to the sun.

Still, we may consider that there is a similarity in the chemical composition of the earth and meteorites. First, the same chemical elements are present on the earth and in meteorites. Second, the relative abundances of the elements are approximately the same; to illustrate, oxygen, iron, magnesium, and silicon are abundant both on the earth and in meteorites, while, for instance, gold and radium are extremely rare in both cases. Third, we find an extremely close similarity in the composition of stony meteorites and the earth; and note that this has to do on the one hand with meteoroids revolving around the sun in orbits that cut across the earth's orbit, and on the other hand, with rocks that comprise the earth's crust.

The mineralogical composition of stony meteorites differs slightly from that of terrestrial rocks. The most common minerals of meteorites are nickel iron, olivine (a magnesium-iron silicate) and pyroxenes (anhydrous silicates). And then there are minerals peculiar only to meteorites—troilite (iron sulphide), schreibersite (phosphorus in a complex compound with iron, nickel, and cobalt), and several others.

The particles of different minerals frequently combine into roundish spherical shapes called chondrules. Meteorites composed of chondrules are known as chondrites. The presence of chondrules indicates that the conditions of meteorite origin differ essentially from those of the origin of terrestrial rocks. Academician A. N. Zavaritsky, a big authority on meteorite structure, believed that chon-

drules could form during the condensation of highly pulverized matter (which already at the onset of pulverization had a complex mineralogical structure) in an area of space with a weak field of gravitation.

Extremely interesting is the presence of carbonaceous compounds and bound water in certain meteorites (for example, the Staroye Boriskino meteorite), which was established by the Soviet woman meteorite worker L. Kvasha. The Staroye Boriskino black chondrite is similar to sedimentary rocks in composition and laminated microstructure. Still, the mineralogical composition of stony meteorites and their structure, like the crystalline structure of iron meteorites, points to special conditions of formation of these cosmic bodies, conditions that are essentially different from those of the formation of terrestrial rocks.

Very important is the isotopic composition of meteorites, which serves as an indicator of the life span of a given assemblage of chemical elements. The composition of meteorites and terrestrial rock, if judged by the ratio of different isotopes of one and the same element, for instance, sulphur or carbon, appears to be almost the same. This sameness in the isotopic composition of meteorites and the earth in addition to their identical chemical composition speaks in favour of a common origin.

Meteorite ages may be determined in the same way as is done with respect to terrestrial rocks, by the ratio of quantities of different isotopes, for instance of argon and potassium, by the ratio of quantities of helium and uranium, of lead-206 with respect to radium and thorium, etc. Extremely interesting data were obtained recently by E. Gerling and K. Rik. Working from a ratio of argon isotopes, they found the age of stony meteorites to range from 600 million to 4,000 million years. Hence, it may be seen that meteorite ages are entirely comparable to the age of terrestrial rocks, and for some meteorites are not less than those of the most ancient

rocks of the earth's crust that belong to the Archeozoic era. Consequently, meteorites originated at roughly the same time as our earth. During this long period of time, a part of the meteorites obviously underwent very considerable changes.

The story of meteorites would not be complete without mention of some remarkable falls in which the meteorites reached the earth's surface with some of their cosmic velocity left. Two such spectacular falls were observed on the territory of the U.S.S.R. this century: the Great Siberian (Tunguska) meteorite of June 30, 1908, and the Sikhote-Alin meteorite of February 12, 1947. Nearly half a century passed before any trace of the Tunguska was found while the Sikhote-Alin meteorite has been studied by Soviet scientists in such detail as probably no other meteorite in the world.

The brilliant fireball that preceded the fall of the Tunguska meteorite was noticed on June 30, 1908, at 7 o'clock in the morning, local time, by the inhabitants of numerous villages in Central Siberia. The peasants at work in the field saw a ball of fire and heard powerful detonations like those of explosions. Correspondents of the Irkutsk Geophysical Observatory reported claps of thunder, a dazzling flare and a dark cloud left in the wake of the fireball. The engineer of a goods train on the Siberian railway near Kansk stopped his train thinking that it had been derailed or that there had been an explosion of material in the cars. Seismographs of the Irkutsk Observatory and of all European seismic stations recorded a powerful quaking of the ground; the air wave circled the globe twice and was registered everywhere by sensitive barographs.

The Tunguska meteorite fell in a remote part of the taiga far from inhabited areas and, despite the great impression it created on those who saw the fireball, it was gradually forgotten. It was only about 20 years later, in 1927, that the U.S.S.R. Academy of Sciences sent

an expedition under the leadership of L. Kulik to study the place of fall of the meteorite. The approximate coordinates of the place of fall determined by Kulik were in good agreement with the site of the epicentre of the earthquake recorded at the Irkutsk Observatory. Around this spot, trees had fallen radially, especially between 5 and 30 kilometres from the point of impact.

A more thorough exploration of the fall area was accomplished by Kulik and Krinov during subsequent expeditions between 1928 and 1930, but not a single trace of the meteorite was found. This circumstance cannot be attributed solely to the insufficient efforts of the members of the expeditions. The absence of big chunks of meteorite or at least of big depressions at the point of impact indicated that the colossal explosion which occurred when the meteorite struck the ground and which was recorded with certainty both by instruments and by eye-witnesses, destroyed the meteorite *in toto*, pulverizing it into minute particles. The significance of the Tunguska fall for science is that it was the first enormous fall that was reliably established by scientists and in sufficient detail.

Through an analysis of seismic observations and a study of barograms of earthquakes and the air wave, it was possible to determine the energy of the explosion and, after obtaining from astronomical observations the velocity of the meteorite, to estimate its original mass, which probably came to several thousands of tons. From observations of the flight path of the fireball and using certain other data, Astapovich and others calculated the orbit of the meteorite.

Only in 1957 did scientists succeed in eliciting a few facts about the meteorite itself. While studying soil samples taken from the fall area in 1927-30 by L. Kulik, Soviet meteoritologist A. Yavnel detected particles of meteoritic matter of size several tens of microns. Chemical analysis showed them to consist of nickel iron,

which means the Tunguska meteorite was of the iron type and, in the explosion, fragmented into tiny pieces. A large number of soil samples have been collected by a new expedition of the U.S.S.R. Academy of Sciences sent to the fall area in 1958. Detailed studies will be made of this material.

Another fall of a giant meteorite occurred on the morning of February 12, 1947, in a desolate region of the taiga that covers the spurs of the Sikhote-Alin mountain ridge. At 10 hours 38 minutes local time (0 hours 38 minutes Greenwich time), a brilliant fireball appeared in the sky. It was brighter than the sun and moved from north to south accompanied by loud sounds that were audible up to 400 km. distance. In its wake the fireball left a dark dust trail in which turbulent phenomena could easily be discerned. This trail took several hours to disperse after the passage of the fireball. It consisted of minute particles of dust that absorbed light rays intensively. The fireball was accompanied by numerous sparks and glowing fragments, especially at the end of its fall. The fall point of the meteorite was detected by aeroplane several days later. It seemed as if the taiga covering the western spurs of the Sikhote-Alin ridge had been subjected to an aerial bombardment. Indeed, numerous craters were found over an area of about 2.5 square kilometres (in the form of an ellipse) on the background of a blanket of snow; around them the trees were felled, broken or torn up by the roots.

The fall region of the Sikhote-Alin meteorite was thoroughly explored in 1947-50 by four expeditions of the U.S.S.R. Academy of Sciences under the leadership of Academician Fesenkov, Krinov and Fonton. Numerous iron fragments, and also craterlets (from 0.5 m. to 28 m. in diameter) produced by the fall were found in the southern part of the dispersion ellipse of the meteoritic shower. In the largest craters the only things found were small pieces of fragmented meteoric material of mass

from fractions of a gramme to several kilogrammes. The largest crater of this type had a diameter of 28 metres and was five metres deep. Large meteorite fragments were found in deep narrow channels which they had dug into the rock to depths of several metres. In the rear (northern) part of the ellipse of dispersion, the meteorite fragments did not form craters but lay right on the surface of the ground. Using sensitive magnetometers and mine detectors, it was possible to collect over 30 tons (256 individual specimens) of iron meteorites. The largest weighs 1,745 kg., and the smallest hundredths of a gramme. Probably a still larger amount of meteoritic iron lies splintered in the ground so that the total mass of fragments of the Sikhote-Alin iron meteoritic shower, as estimated by Academician Fesenkov, is approximately 100 tons. Since an enormous amount of meteoritic matter was pulverized in the passage through the atmosphere, the initial mass of the meteorite was probably not less than several hundreds of tons. It was very likely a miniature asteroid that entered the earth's atmosphere at the relatively small speed of 14 to 15 km./sec. The meteorite fragments consist of huge crystals of nickel iron differently oriented and relatively weakly bound together. Splintering and fragmentation of the meteorite disrupted these bonds so that the separate fragments are somewhat like druses of nickel-iron crystals.

The surface of these druses was intensely polished by the air, has a series of depressions (regmaglyptes) and is covered with a dark fusion crust. Polished sections of the meteorite clearly exhibit the fine crystalline structure of nickel iron in the form of Neumann lines. The Sikhote-Alin meteorite is composed of iron (93 per cent), nickel (5 per cent), and also phosphorus, sulphur, cobalt, copper, chromium, and other chemical elements.

From the foregoing description it is obvious that at

the end of its trajectory the Sikhote-Alin meteorite had only the remnants of cosmic velocity, probably of the order of 0.5-1 km./sec., and produced effects similar to those of an explosion. The energy of the meteorite was consumed in the formation of craters; pieces with the greatest amount of kinetic energy ejected huge masses of soil and were shattered into tiny fragments. Meteorite fragments of lower kinetic energy dug into the ground forming shallow depressions and craterlets and remained intact. There was no real explosion in the form of a sudden expansion of compressed gas; however, after the impact, the velocities of the fragments were distributed exactly as is observed in the transmission of explosive momentum to a large number of small particles. The larger fragments moved at relatively low speeds, while small particles acquired high speeds and considerable kinetic energy. The phenomenon of crater formation in the fall of the iron Sikhote-Alin meteorite shower occupies an intermediate position between the formation of simple depressions by meteorites falling from the delay region with a low speed and the explosive phenomena that accompany the impact of such meteorites as the Tunguska.

If a meteorite, on impact, has a large velocity (of the order of 4 km./sec. and more), its energy is sufficient to destroy the structure of the solid body and convert considerable quantities of the meteoritic material and the soil into a highly compressed gas. Stanyukovich and the author showed in 1948 that the volume of material converted to gas may exceed that of the meteorite by tens and hundreds of times. The sudden expansion of the gas produced leads to an explosion. The result is a crater with a diameter that can be hundreds of times the size of the crater-forming meteorite.

On the surface of the earth we find craters produced by meteorites that were not observed during their falls. First on this list are the Arizona and Quebec craters in North

America, the Kalliyarvi crater in Estonia (U.S.S.R.), Henbury in Australia, Wabar in Arabia, and some others. The Arizona crater, 1,200 metres in diameter and 175 metres deep, has been described many times in the specialized and popular scientific literature. Numerous fragments of iron meteorites with a clear-cut crystalline structure have been found near its rim. But neither drill holes, nor magnetometer surveys have revealed any big meteoritic mass that can correspond to the dimensions of the Arizona crater. Possibly the explosion of a chunk of iron 10 to 30 metres in diameter and weighing 100,000 tons could produce the Arizona crater.

The Kalliyarvi meteorite crater on Saarema Island has been thoroughly studied and described by the Estonian geologist N. Reinvald. Its dimensions are far more modest: 100 metres across and six metres deep. Here too, many small fragments of iron meteorites were found around its rim. The Henbury meteorite craters in a desert area of Central Australia are 13 roundish depressions of diameter between nine and 200 metres, and depths to 15 metres. Four fragments of meteorite nickel-iron were found in the smallest crater.

The destructive action of the impacts of crater-forming meteorites on the face of our planet is negligible. But for other planets and their satellites which are not protected, like the earth, with an atmosphere, the results of meteoritic impacts should be considerably greater. The surface of the moon with its multiplicity of craters, partly volcanic and partly meteoritic in origin, has been shown by Sytinskaya to be covered with a thick layer of dust. This may be inferred from its colour and its reflectivity (both as regards light rays and radio waves). This dust originates from meteoritic bombardment. The surface features of other bodies in the solar system should also be affected by the destructive action of collisions with meteorites.

7. METEORIC MATTER IN THE SOLAR SYSTEM

Up till now our study of meteoric bodies has been restricted to meteors glowing in the upper atmosphere as observed from the earth or to bodies that reach the earth's surface in the form of meteorites. It is this last stage in the life of meteoroids that enables us to get all the information that can be obtained. Outside the earth's atmosphere we are not able to detect the tiny meteoric particles and study their properties. Nevertheless, by analyzing the observational data of meteors when they collide with the earth it is possible to gain extremely important and rather extensive information about their cosmic nature, and their place and role in the solar system.

The transition from meteor distribution (as it appears to the terrestrial observer) according to brightness, numbers, velocities, etc., to the actual distribution in the solar system is the principal task of meteor astronomy. This task is extremely complicated due to the fact that the conditions of meteor visibility depend on a whole series of factors whose influence is exceedingly difficult to account for. In this respect, the science of meteors is at a disadvantage when compared with other branches of astronomy, for instance, solar physics, or the physics of the planets and stars, where the observer is able to encompass complete phenomena even though the latter are to some extent distorted. This explains why, in the history of meteor astronomy, big mistakes have been made even by prominent investigators. Such, for example, are hypotheses concerning a uniform distribution of directions of meteoroid movements in space or the interstellar origin of a considerable part of meteoric matter.

The first question, which refers to the cosmic nature of meteoric matter, is that of the number, spatial density, and mass of meteoroids. To answer it, we must find out the actual number of meteors that fall each day. The

method of counting here is rather simple. From radar data it is known that the mean meteor height is 87 km. Let the radius of the observer's field of view inside which he notes all meteors of zero to second magnitude be 25°. We can then calculate the area covered by this field of view at height of 87 km. It comes out to approximately 5,000 sq. km. whereas the area of the whole globe is 5×10^8 sq. km. If the hourly number of meteors of, say, second magnitude is 1.2, the true diurnal number N of such meteors will, for the earth as a whole, be:

$$N = 1.2 \frac{5 \times 10^8}{5 \times 10^3} \times 24 = 2.9 \times 10^6$$

In this way we obtain data concerning the true number of meteors as given in Table 1.

Table 1

True Diurnal Number of Meteors (earth as a whole)

Apparent stellar magnitude, m.	Observed hourly number, n	True diurnal number, N	lg N
—3	0.012	$28 \cdot 10^3$	4.45
—2	0.03	71	4.85
—1	0.08	180	5.26
0	0.19	450	5.65
1	0.46	$1.1 \cdot 10^6$	6.04
2	1.2	2.8	6.45
3	2.7	7.1	6.85
4	3.8	18	7.26
5	1.5	45	7.65
6	—	110	8.04
7	0.14	240	8.38
8	0.08	410	8.61
9	0.15	$1.2 \cdot 10^9$	9.62
10	0.14	4.5	9.65
11	0.06	6.4	9.81

These results are the revision of a table, first compiled by the American astronomer F. Watson in 1941, with account taken of data on telescopic meteors of the Stalinabad astronomer A. Bakharev.

It is easy to see that the number of meteors of each given magnitude is greater by a factor of 2.5 than the preceding magnitude. This ratio is brilliantly confirmed by radar observations. However, this mean ratio as derived for the overall total number of meteors that encounter the earth does not hold in the case of separate meteor showers.

The mean meteor density in interplanetary space near the earth is equal to the diurnal number of meteors of a given magnitude divided by the volume of space that the earth sweeps out every 24 hours. Simple calculations show that the density of meteoric matter in interplanetary space is negligible, amounting to 1.4×10^{-24} particle per $cm.^3$ for meteors of zero magnitude, that is to say, roughly one particle within a cube one edge of which is 1,000 kilometres. Even for meteors of tenth magnitude there is one meteoric particle in a cube with an edge of 40 kilometres.

Above we mentioned that the mass of a meteor of zero magnitude is estimated at an average of the order of one gramme and that the mass of a meteor of each succeeding magnitude is less by a factor of 2.5. Since the number of meteors of each magnitude is 2.5 times that of the preceding magnitude, the total mass of meteors of a given magnitude that encounters the earth daily is a constant value and may be estimated in round figures at 0.5 ton. We are now in a position to evaluate the total mass of meteoric matter that falls on the earth every day. Meteoric findings suggest that the total mass of meteorites associated with fireballs of minus tenth magnitude and brighter is roughly equal to one ton. At the other extreme are meteors fainter than thirtieth magnitude, which are dust particles swept out of the solar system by the sun's radiation pressure. This is why such meteors cannot exist in the solar system. Summarizing, we find the total mass of meteoric matter

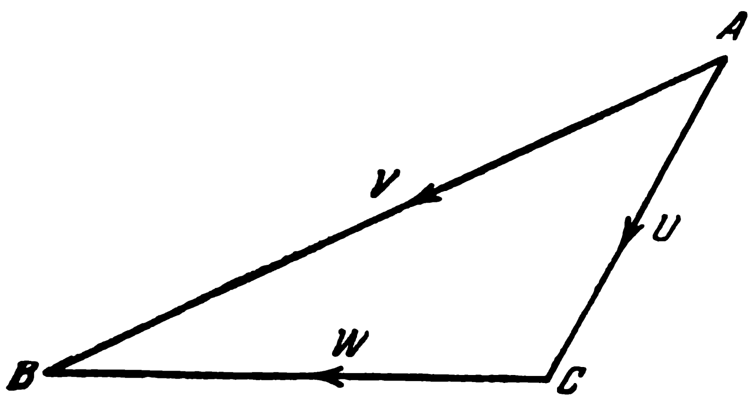


Fig. 21. The heliocentric *(V)* and geocentric *(U)* velocities of meteors; *W* is the velocity of the earth in its orbit

that falls to earth daily to be about 20 tons, or several thousand tons per year. This is an insignificant mass that has not been capable of altering essentially the face of the earth or even affecting perceptibly the rate of the earth's rotational period during the 2,000 million years that have passed since the formation of the crust of the earth.* This calculation, it is true, does not take into account the mass of very tiny meteoric dust particles that enter the atmosphere at very low speeds relative to the earth without producing noticeable glow. It has been noted that artificial satellites make possible a direct measurement of the number of micrometeorites that will make impact with a rocket. This number is then easily recalculated for the earth as a whole. On May 27, 1958, when an earth satellite fired from Canaveral, Florida, failed to orbit, the mass of meteoric matter that fell to earth in 24 hours was in agreement with the previous estimate of 25 tons, but other American experiments give much bigger figures. M. Debin reports the mass of meteoric matter that fell to earth in 24 hours in February 1958 at 3,300 tons, while the estimate for October 1957 was 10,000 to 20,000 tons. These latter figures are of the same order of magnitude as the estimates of cosmic dust that falls on earth given by different investigators (between 1,500 and 6,000 tons per 24 hours). The spatial density of meteoric matter in the vicinity of the earth's orbit may be determined from the above

* According to the laws of theoretical mechanics, an increase in the mass of a body reduces its speed of rotation.

reasoning. It comes out to something between 10^{-21} and 10^{-23} gr./cm.^{3}

When meteors encounter the earth their geocentric velocity results from combining the velocity of the earth and that of the meteors relative to the sun (their heliocentric velocity) (Fig. 21). The direction of motion of meteors, relative to the earth, is characterized by the angular distance (elongation) of the radiant from the point towards which the earth is moving (apex). Since observed geocentric meteor velocities lie within the range from 10 to 71 km./sec., and the velocity of the earth is 30 km./sec., the heliocentric velocity of a meteor does not exceed 41 km./sec., which means that it is less than the parabolic velocity. Consequently, all meteor orbits around the sun are closed elliptical orbits.

On the other hand, meteor velocities may be evaluated not from observations, but statistically, as proposed by Schiaparelli (Italy) and developed by Hoffmeister (Germany). Let us suppose that all directions of meteor motions in the vicinity of the earth are equally probable. When the apex is high above the horizon there should be a larger number of meteors in the celestial hemisphere visible to the observer, since above the horizon we see the majority of head-on meteors and also meteors moving more slowly than the earth and swept up by the latter. And, on the contrary, when the antiapex (that is, the point away from which the earth is moving) is above the horizon and the observer sees in his celestial hemisphere only meteors catching up with the earth, their number should be smaller. If meteors were stationary relative to the sun, the ratio of the number of catching-up and head-on meteors would equal to zero; if meteors possessed infinite velocity, this ratio would convert to unity. For all intermediate values of the mean heliocentric velocities of meteors (on the condition of equal probability of different directions) we will have a value of this ratio less than unity, the

number of overtaking meteors being less than the number of head-on meteors.

The apex moves over the sky due to the diurnal and annual movements of the earth: at 6 a. m. local time the apex is in its highest position above the horizon with respect to the observation point; in autumn it is at the highest point of the ecliptic (in September for the northern hemisphere of the earth, and in March for the southern hemisphere). For this reason, there should be diurnal and annual variations in the number of meteors that do not belong to any definite meteor shower and therefore do not possess a preferential direction of movement (sporadic meteors).

Using the old observations of Coulvier-Gravier, Paris watchmaker and amateur astronomer who carried out his meteor observations over a hundred years ago, Schiaparelli estimated the mean velocity of sporadic meteors as parabolic. The more precise observations of Hoffmeister in the first half of the twentieth century showed that the heliocentric velocity of meteors thus found exceeds appreciably the parabolic velocity.

Hence, it could be concluded that sporadic meteors should be arriving in the solar system from interstellar space along hyperbolic orbits. Such in reality was the conclusion that Hoffmeister and others in the 1920's and 1930's drew from statistical observations. Precise photographic and radar determinations of meteor velocities had not yet been made and this erroneous conclusion was long accepted by many astronomers.

An interstellar origin was attributed even to such meteor showers as the Lyrids and Taurids, for which elliptical orbits had earlier been supposed and later firmly established. However, later, Astapovich in the U.S.S.R., and Prentice and Porter in England began to doubt Hoffmeister's conclusions even on the basis of visual observations alone. These workers concluded that the greater part of the meteoric orbits is elliptical. The controversy was final-

ly settled by precise photographic and radar observations. The results of these observations clearly showed the ellipticity of the orbits both of sporadic meteors, including telescopic meteors (up to the eighth magnitude) and of shower meteors.

The contradiction between the results of meteor velocity determinations by statistical and other methods finds its sole explanation in the incorrect premises used to interpret the counting of meteors. Indeed, the supposition concerning uniform distribution, in space, of the directions of motion of sporadic meteors is erroneous. The bulk of the meteors move around the sun in the same direction as all the planets (including the earth). Therefore, the majority of the meteors are overtaking the earth as they move around the sun in the same direction as the earth. This explains the relatively large number of meteors in the celestial hemisphere turned towards the antiapex, which leads to an exaggeration of meteoric speeds. Levin, working from his own physical theory of meteors, has shown that head-on meteors with high geocentric velocities should glow much brighter than overtaking meteors. Many of this latter class of meteors are very faint, and for this reason, for equal apparent brightness, the number of head-on meteors appears relatively large. If we take into account Levin's argument, it appears that nearly 99 per cent of all the meteors have a direct motion (the same as the earth) and are overtaking the latter.

To summarize, it is now firmly established that meteoroids in the solar system move in one and the same direction, following the rotation of the sun itself and the revolution of all planets around the sun. In itself this conclusion is of extraordinary significance since it is proof of a common origin for the entire solar system, which includes the cloud of meteoric material as one of its component parts.

Just recently, mass-scale radar determinations of the velocities and directions of motion of separate meteors

have made it possible to ascertain more accurately the nature of the orbits of sporadic meteors encountering the earth. According to data obtained by Davies at the Jodrell Bank Radio Observatory in 1954, the majority of meteors move in elliptic orbits with periods of 0.5 to 10 years. The greatest number of meteors have periods of revolution about the sun of about three years. The radiants of sporadic meteors are spread over the entire visible celestial sphere since their orbits are inclined to the plane of the earth's orbit (ecliptic) at every possible angle. These data are in good agreement with the less numerous photographic determinations of meteor orbits made by L. Katasev in the U.S.S.R., and F. Whipple and L. Jacchia in the U.S.A.

What is the distribution of meteoric matter in the solar system? Only a very approximate answer can be given to this query, for we are acquainted only with those meteors that approach the earth in their movement around the sun, or, more precisely, whose orbits intersect the earth's orbit. The result is that we can study only a very small class of meteor orbits, and to draw therefrom conclusions about the whole assemblage of meteoric bodies in the solar system is a rather difficult task. However, it is quite natural to suppose that the density of meteoric matter diminishes with distance from the sun, that meteoric matter is predominant in the plane of the ecliptic, that is, in the plane of the planetary orbits, and that there may be qualitative changes in the composition of particles of the meteoric cloud as one moves away from the sun. The first two points are supported by factual data on the zodiacal light, which is seen as a faintly glowing cone situated along the ecliptic. In the opinion of Fesenkov and other workers, the zodiacal light is the result of reflection and scattering of the sun's light by minute particles of the meteoric cloud. The shape of the zodiacal light confirms the supposition that the meteoric cloud should be in the shape of a lens lying in a plane close to the planes of the orbits of the planets of the solar system.

Table 2

Meteor Spectra

Element	Percentage of spectra in which lines of given element are detected
Iron	85
Calcium (ionized)	77
Calcium (neutral)	40
Manganese	21
Magnesium	17
Chromium	17
Nickel	6
Aluminium	6
Magnesium (ionized)	4
Silicon (ionized)	4
Titanium	2
Cobalt	2
Sodium	2

The chemical composition of meteors can be judged from the lines of elements detected in meteoric spectra. The spectra of meteors may be divided into two types. The first has strong lines of calcium, while the second has characteristic lines of iron. The remaining spectral lines are distinguished in meteor spectra by their positions relative to the lines of calcium and iron. The Type I spectra are the most common—75 per cent of all cases. Besides lines of calcium, they contain the lines of iron, chromium, aluminium, nickel, silicon, manganese, magnesium, sodium, titanium, and cobalt. Thus, meteors whose luminescence produces Type I spectra are identical with stony meteorites as far as chemical composition goes.

Type II spectra are encountered in only 25 per cent of all cases, contain lines of iron and nickel and are produced by the luminescence of iron bodies that correspond in every way to iron meteorites. Hence, the conclusion should be drawn that meteorites and the smaller meteoric bodies

are similar in chemical composition, comprising a sequential series.

However, the chemical composition of meteors should experience variations depending on their distance from the sun, because solar heat causes the more volatile substances to evaporate from them. This is why meteoroids revolving near the sun, for example near the orbit of Mercury, may be expected to have lost sodium, magnesium and possibly other elements through volatilization, whereas meteoroids in the outer parts of the solar system, where the heat from the sun is slight and the temperature low, can consist, in large measure, of ices of ammonia, carbon dioxide, etc., whose boiling temperatures are below the space temperature in these regions.

Such in general outline is the nature of the meteoric cloud in the solar system. The question of the origin of the meteoric cloud requires a study of interrelationships between meteors and the other bodies of the solar system.

8. METEOR STREAMS

The assemblage of meteoric material in the solar system even in its general form, appears as a system. Individual meteors move around the sun in closed orbits and in the same direction as the larger bodies of the solar system—the planets and their satellites. This picture becomes still more regular and orderly if we recall that whole swarms of meteors are moving in common orbits that form more or less sizeable meteor streams. These streams are easily recognized in observations from the earth. The meteors that belong to one and the same swarm move in parallel paths, and to an observer they appear to emerge from a single point in the sky, the so-called radiant. Radar has made it possible to extend considerably our knowledge about meteor streams through the discovery of so-called day-time streams whose radiants appear above the observer's horizon only in the day-time.

Table 3

Meteor Showers

No.	Shower	Epoch of activity	Date of maximum	Radiant α δ	Closest star
1.	Quadrantids	27/XII-7/I	3/I	231°+52°	ι Draconis
2.	—	12/III-5/IV	25/III	184—27	β Corvi
3.	—	1-5/IV	3/IV	280—35	δ Sagittarii
4.	Lyrids	15-26/IV	22/IV	272+33	α Lyrae
5.	Virginids	March-May	3/IV	200— 6	α Virginis
6.	Gamma Aquarids	28/IV-12/V	5/V	335— 1	η Aquarii
7.	—	8-9/VI	—	227—28	γ Scorpii
8.	Bootids	18/VI-8/VII	29/VI	200+55	ζ Ursae Majoris
9.	Scorpionids-Sagittarids	May-July	14/VI	270—30	γ Sagittarii
10.	Delta Aquarids	22/VII-9/VIII	23/VII	338—12	δ Aquarii
11.	—	27-31/VII	29/VII	346—58	γ Tucanae
12.	—	19-31/VII	26/VII	341+21	λ Pegasi
13.	Perseids	16/VII-22/VIII	11-12/VIII	46+56	γ Persei
14.	Aurigids	29-31/VIII	30/VIII	86+41	ϑ Aurigae
15.	—	15-25/VIII	20/VIII	291+52	ι Cygni
16.	Cassiopeids	19/VII-15/VIII	28/VIII	14+63	β Cassiopeiae
17.	—	16-24/VIII	20/VIII	311+62	η Cephei
18.	Draconids	8-12/X	9/X	268+60	ζ Draconis
19.	Taurids	October-November	—	58+20	γ Tauri
20.	Orionids	14-26/X	21-22/X	90+14	α Orionis
21.	Arietids	October-November	14/X	30+25	α Arietis
22.	Leonids	10-18/XI	16/XI	150+20	γ Leonis
23.	Andromedids	15-27/XI	17/XI	25+42	γ Andromedae
24.	Geminids	1-17/XII	14/XII	112+33	α Geminorum
25.	Ursids	19-26/XII	22/XII	233+83	β Ursae Minoris
26.	—	5/XII-7/I	29/XII	149—51	Velorum

Visual observations established the existence of several tens of sufficiently clearly defined night-time meteor showers. Information on the most active streams is sum-

marized in Table 3 (p. 81), where the position of the radiant is defined by its celestial coordinates: right ascension (α) and declination (δ).

The names of the meteor showers are due to the constellations in which their radiants are located. In the U.S.S.R., it is possible to observe all radiants of the northern hemisphere and some of the radiants of the southern hemisphere, up to about 40° south declination. The radiants of the southern hemisphere of the sky can be studied from points in the southern regions of the Soviet Union.

Radar observations of night-time meteor showers have shown the possibility of sufficiently accurate determinations of their radiants by this method. Table 4 compares data on radiants obtained for big night-time meteor showers visually and by radar.

Table 4

Visual and Radar Observations of Night-Time Meteor Showers

No.	Shower	Data	Co-ordinates of radiant	
			Visual α δ	Radar observations α δ
1.	Quadrantids	Jan. 3	231° +52°	232° +50°
2.	Lyrids	Apr. 22	272+33	273+30
3.	Gamma Aquarids	May 6	335— 1	338+ 3
4.	Delta Aquarids	July 28	338—12	338— 7
5.	Perseids	Aug. 12	46+56	46+57
6.	Arietids	Oct. 14	30+25	37+ 4
7.	Orionids	Oct. 22	90+14	96+11
8.	Taurids	Nov. 9	58+20	55+25
9	Geminids	Dec. 14	112+33	115+32
10	Ursids	Dec. 22	233+83	202+78

According to meteor radio observations, the geocentric velocity for the Quadrantids is 37.1±3.5 km./sec., for the

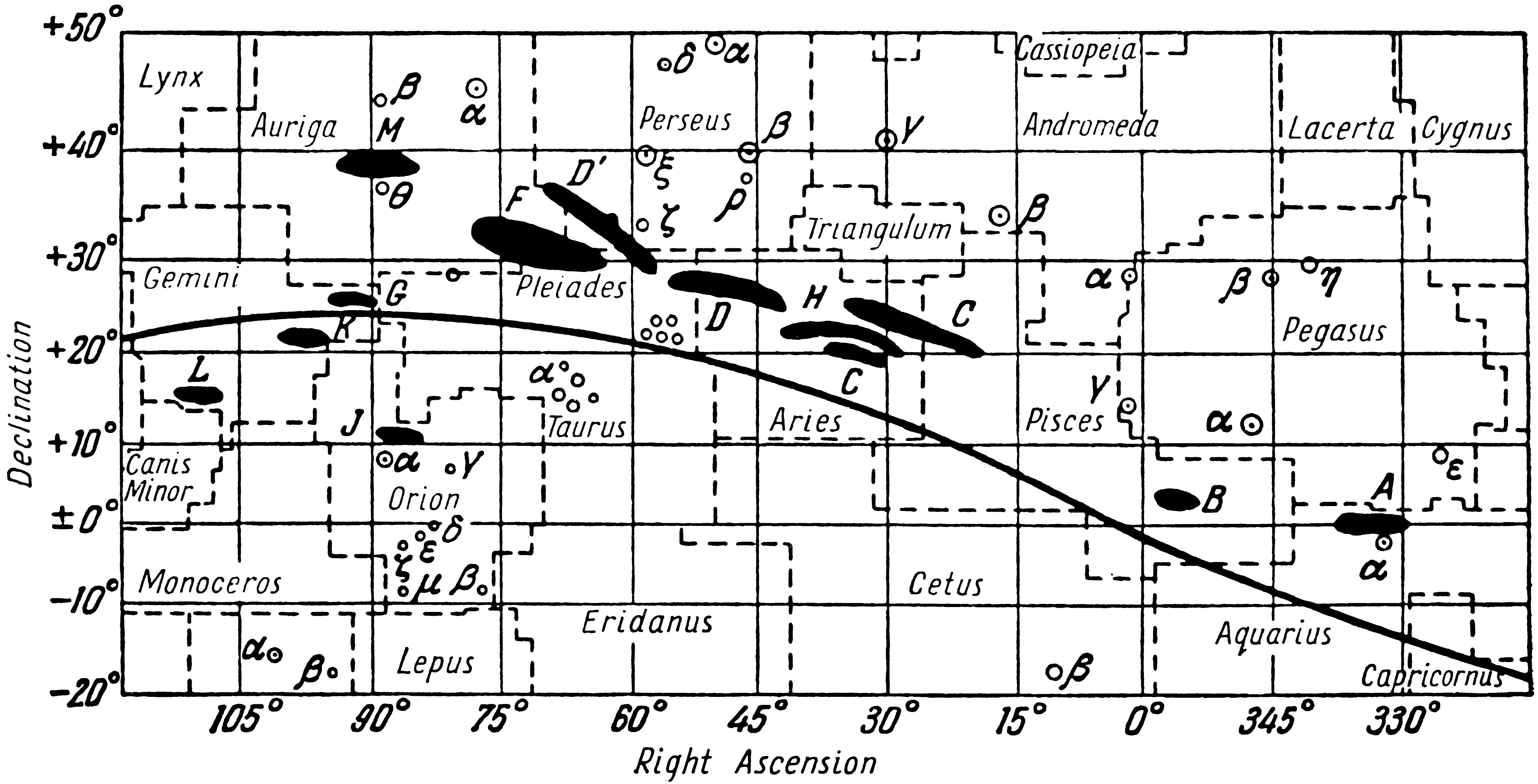


Fig. 22. Radiants of day-time meteor streams (taken from radar observations)

Perseids 60.1±4.0 km./sec., for the Geminids 35.9±4.6 km./sec.

Radar observations not only give the radiant positions of meteor showers with an accuracy nearly equal to visual determinations, but also permit ascertaining the geocentric velocity of the most active of them, that is, finding their orbits. For this reason, information, about day-time meteor streams obtained exclusively by radar are fully reliable. Table 5 is a list of the day-time meteor showers discovered during recent years (Fig. 22).

Table 5

Day-Time Meteor Showers

No.	Constellation or closest star	Date of maximum	Radiant position α δ	Hourly rate	Geocentric velocity (km./sec.)
1.	ζ Persei	June 3	61.5°+24.4°	40	28.8
2.	Aries	June 8	44.3+22.6	60	37.6
3.	β Tauri	July 2	86.2+18.7	30	31.5
4.	Pisces	May 7-13	20+25	30	—
5.	o Ceti	May 21	30—3	20	—
6.	54 Persei . . .	June 25	68+33	50	—
7.	α Orionis . . .	July 12	87+11	50	—
8.	ν Geminorum .	July 12	98+21	60	—
9.	λ Geminorum .	July 12	111+15	32	—
10.	θ Aurigae . . .	July 25	87 +38	20	—

The first three showers are most reliable, the others have been observed only once or twice and require further regular observations. Round-the-year radio observations of the number of meteors indicate that the day-time meteor showers in May and June are the most intensive, exceeding even those like the Perseids and Geminids. Of course, this does not include sudden and rich displays of meteors from individual radiants. In recent years (1933 and 1946) the Draconids produced such storms of meteors.

With a knowledge of the radiant, that is, the direction of motion of the meteors relative to the earth, and their

geocentric velocity it is possible to derive the orbits of meteor streams. The orbit of a meteor stream, like that of any body of the solar system, can be described by six elements which determine, first, the mutual position of the planes of the orbits of the stream and the earth, second, the shape and position of the orbital ellipse in this plane, and, third, the time of passage of the meteors through perihelion (closest approach to the sun; the opposite point—the greatest distance from the sun—is called the aphelion).

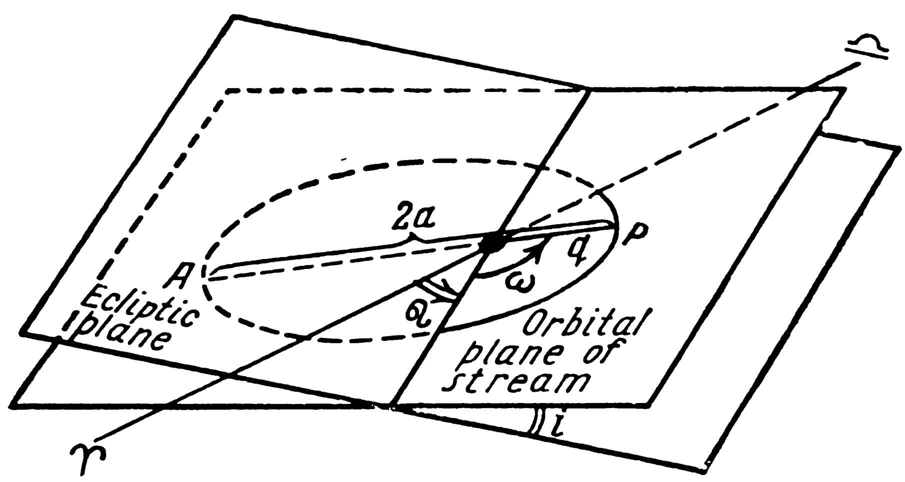


Fig. 23. Orbital elements of a meteor stream. *P*—perihelion, *A*—aphelion, ♈ —towards point of vernal equinox, ♎ --towards point of autumnal equinox

Thus, to determine the shape and position in space of the orbit of a meteor stream we must define five elements: inclination of the orbital plane to the ecliptic (i); longitude of the ascending node (☊) which is the angular distance in the plane of the ecliptic from the point of the vernal equinox (♈) to the point of intersection of the planes of the earth's orbit and the orbit of the meteor stream; the angular distance along the orbit from the ascending node to the direction of perihelion (ω); the distance of the stream from the sun at perihelion (q) expressed in astronomical units, or the semi-major axis of the orbit (a); the eccentricity of the orbit (e), the value of which for ellipses lies between 0 and 1. The period of revolution about the sun (P) is related to the value of the semi-major axis

of the orbit by Kepler's third law: $P = a^{3/2}$. The time of perihelion passage, which is ordinarily calculated for planets and comets, is not defined for meteor streams since it is of no interest.

Below we give the elements of several major meteor streams.

Table 6

Orbital Elements of the Major Meteor Streams

Stream	V_g (km./sec.)	☊	ω	i	e	q	a
Perseids . . .	60.5±4.6	139°.5	153°	114°	0.93	0.97	14.4 Radio
"	58.7	139.4	150	113.5	0.89	0.96	9.1 Photo
Geminids . .	35.7±4.6	262.2	325	23	0.89	0.14	1.31 Radio
"	35.1	262	324	23	0.91	0.14	1.24 Photo
Guadrantids .	35.1—3.4	282.5	166	67	0.46	0.97	1.8 Radio
"	48	282.1	168	74	0.72	0.93	3.4 Photo
Leonids . . .	72	233	179	163	0.90	0.99	10.0 Visual
Lyrids* . . .	51	30	213	80	1.0?	0.90	— Photo
Andromedids	16.8	242	227	12	0.79	0.86	4.0 "
Gamma Aquarids . . .	66	45	100	162	0.97	0.60	? Visual
Orionids . . .	68	28	143	161	0.97	0.57	? "
Draconids . .	20	196	175	31	0.71	1.02	3.5 "
Taurids . . .	27.3	47	109	4	0.82	0.39	2.2 Photo
Delta Aquarids* . . .	50	305	—	56	1.0?	0.04	? Visual
Cassiopeids* .	50	135	335	87	1.0?	0.97	? Photo

Meteor streams with definitive orbits may be divided into three groups. The first group includes meteor streams with aphelia far beyond Jupiter's orbit. The orbits of these streams are highly elongated and inclined to the plane of the ecliptic at considerable angles which at times exceed 90° (in the case of retrograde motion). The periods of such

* The orbit is assumed parabolic due to lack of knowledge of the heliocentric velocities of the meteors or of their periods.

streams are reckoned in tens of years. Such are the Lyrids, Gamma Aquarids, Orionids, Perseids, and Leonids.

In the second group are meteor streams with aphelia close to the orbit of Jupiter. These orbits are but slightly inclined towards the plane of the ecliptic. This group of streams is constantly being perturbed by Jupiter and comprises the so-called Jovian family. They are the Andromedids, Bootids, and Draconids. These streams have periods of several years. The conditions for viewing these streams from the earth vary considerably due to the fact that each approach to Jupiter rather appreciably alters their orbits.

The third group comprises a family of orbits of streams located near the earth's orbit. The meteors of this group move in the same direction as the earth and their orbits are only slightly inclined to the ecliptic. They include the Quadrantids, Virginids, Delta Aquarids, Scorpionids, Geminids, and very rich day-time meteor showers. They have periods that range from one to three years. Among the meteoroids revolving close to the earth's orbit there are some relatively large bodies that produce bright fireballs. The meteor streams of the third group are overtaking the earth and so have a low geocentric velocity.

Judged by the distribution of meteoric matter along the orbit, all meteor streams may be divided into two classes. Class one includes meteor streams with a clearly defined concentration of meteors in a certain part of the orbit. Annual encounters with the earth produce weak showers. But when the earth encounters the main swarm the result is a real meteor storm. The streams in this class are the Lyrids, Leonids, Draconids, and Andromedids (Bielids). In these streams, the main mass of meteoric material is concentrated in compact swarms with only a small number of meteors scattered along the remaining part of the orbit.

Other streams (class two) have their meteoric matter spread out rather uniformly along the whole orbit, producing something in the nature of a doughnut spinning round the sun. A typical example of such a meteor stream

is the Perseids, which are observed annually in just about the same quantities. The majority of the meteor streams belong to this second class.

The spatial density of meteoric matter in streams is higher than the mean density of sporadic meteors. However, even in such abundant streams as the Perseids or Geminids, there is an average of one meteor-producing particle visible to the naked eye in a cubic volume of space with an edge 100 to 120 kilometres. And only in the most dense parts of the meteor streams of the first group, when the hourly rate reaches several thousands of meteors, does the distance between such particles fall to 30 and even to 15 km., as was the case during the Leonid meteor shower of 1833.

The mass distribution of particles in streams differs considerably from the distribution for sporadic meteor material. According to Hoffmeister's data, the quantity n which shows the number of times the quantity of meteoric particles increases from one magnitude to the next, is specific for each meteor stream and varies from 4.0 for the Orionids to 1.7 for the Lyrids. More precise radar observations embracing meteors to the eighth and ninth magnitude give a value of n for the Perseids, Geminids, and Quadrantids that fluctuates between 1.7 and 1.9. This indicates that a considerable part of these meteor streams consist predominantly of relatively large meteoroids. On the other hand, some of the meteor streams, as for instance, the earlier-mentioned Orionids ($n=4$) or the Arietids ($n=3.2$), are, on the contrary, relatively rich in small particles. This circumstance testifies to different ages for meteor streams that are at different stages in their development.

Of great interest is the structure of meteor streams. To get an idea of the spatial structure of streams we must know the distribution of meteoric particles along the central (axial) line and also in cross section. Some idea of the cross sectional structure of a stream may be had by observing the meteors in a shower day by day from their first appearance till their complete disappearance. In a

number of cases this cross section is very great. Suffice it to say that it takes the earth a month to cross the Perseid stream, which suggests a diameter for the stream of about 80 million kilometres. On the other hand, some meteor streams, such as the Draconids, have a comparatively compact central condensation with a diameter of only about one million kilometres.

The mass distribution of meteors in the stream is not uniform either. Thus, it is a well-known fact that the largest meteoric bodies are on the axial line of the Perseid stream so that in an epoch of maximum the relative number of bright meteors increases noticeably. Such streams as the Scorpionids, Taurids, and others contain a large number of large-size bodies that produce brilliant fireballs.

If we know the density of meteoric matter in the streams and the mass of the individual bodies, it is possible to calculate the total mass of the stream. The Perseid stream has a mass of about 10^{10} tons, which is less than that of the earth by a factor of 10^{12}. All streams taken together have a total mass probably of the order of 10^{-10}-10^{-11} that of the earth. Thus, the meteoric matter contained in the visible streams comprises a negligible portion (about 10^{-16}) of the total mass of the solar system.

Some big meteor streams have orbits very similar to those of big comets and are undoubtedly related to the latter. At present there has been established or is suspected an interrelationship between something like 90 comets and related meteor streams.

The most reliable and detailed study of relationship between comets and meteor streams has been made for the ten streams listed in Table 7.

Let us now review the major meteor showers. One of the best studied showers is the night-time Perseids observed annually in August. Besides a highly active central radiant, this shower has a large number of subsidiary radiants so that the total area of radiation of the Perseids has a radius of over 20°. The central radiant is located at

Table 7

Interrelationship of Meteor Streams and Comets

No.	Stream	Comet	No.	Stream	Comet
1.	Lyrids	1861 I	6.	Bootids	1951 VI Pons-Winnecke
2.	Gamma Aquarids	1910 II Halley	7.	Draconids	1946 V Giacobini-Zinner
3.	Orionids . . .	1910 II Halley			
4.	Perseids	1862 III Swift-Tuttle	8.	Aurigids	1911 II Kies
5.	Leonids	1866 I Tempel	9.	Andromedids	1852 III Biela
			10.	Taurids	1954 IX Encke

a point in the sky with coordinates $\alpha = 46°$, $\delta = +50°$ (for August 12). The Perseid radiant shifts from day to day due to the fact that the earth, moving in an elliptical orbit, meets the stream each day in a slightly different direction from that of the previous or subsequent days. The daily displacement of the Perseid radiant amounts to $\Delta\alpha = +1.2°$, $\Delta\delta = 0.0°$ according to visual data and $\Delta\alpha = +0.7°$, $\Delta\delta = +0.1°$ according to photographic and radar data. An active branch in the stream (aside from the central radiant) is the eastern radiant of the Perseids: $\alpha = 25°$, $\delta = +47°$. The orbits of the central and eastern branches of the Perseids are close to the orbits of Comets 1862 III and 1870 I, as may be seen from Table 8.

On the basis of a rough coincidence of the central and eastern branches of the Perseids with the orbits of Comet 1862 III and Comet 1870 I, we may conclude that they have a common origin. However, this common origin cannot be explained as a simple disintegration of these comets into meteors, since the Perseids have been observed now for over 1,100 years.

Another remarkable shower is the Leonids, which have been on display for over 3,770 years. In the eighteenth and

Table 8

The Perseid Orbit

Orbital elements	Perseids (Central branch)	Comet 1862 III	Perseids (Eastern branch)	Comet 1870 I
☊	139°	138°	139°	142°
i	114	114	123	122
e	0.93	0.96	1.00	1.00
q	0.96	0.96	1.01	1.01
P	110 years	122 years	—	—

nineteenth centuries the Leonids produced periodic showers every 33 years (1766, 1799, 1833, 1866), which made it possible to compute the period of the stream and to define its orbit, which turned out to be very similar to that of Comet 1866 I.

Table 9

Leonid Orbit

Orbital elements	Leonids	Comet 1866 I
☊	233°	231°
i	163	163
e	0.90	0.90
q	0.99	0.98
P	33.2 years	33.2 years

Since the end of last century the orbit of the stream has receded from that of the earth due to planetary perturbations, and at present the Leonids are very poor in meteors during the period of their activity (November 10-18). The area of Leonid radiation is much smaller than that of the Perseids.

From among the other meteor streams of the first group, the Lyrids (observed April 20-26) have from time to time produced a rich display of meteors. Their orbit is close to that of Comet 1861 I. The last magnificent Lyrid display was observed on the night of April 22-23, 1922, in the European part of the U.S.S.R. Ordinarily this shower is rather meagre.

A large number of meteors are produced annually by a stream with an orbit close to that of Halley's comet (1910 II). It encounters the earth twice: May 1-5 as the Gamma Aquarids, and a half year later, October 20-25, as the Orionids. In May the radiant of the Gamma Aquarids is close to the sun thus making visual observations difficult. At this time the most convenient method of study is by radar.

Table 10

The Orbits of Gamma Aquarids and Orionids

Orbital elements	Gamma Aquarids	Orionids	Comet Halley 1910 II
☊	45°	28°	57°
i	162	161	162
e	0.97	0.97	0.97
q	0.60	0.57	0.59
P	76 years	76 years	76 years

Due to big inclinations of orbits and long periods, the meteor streams of the first group are less influenced by various perturbations of the major planets and are steadily observed over hundreds and thousands of years, as witness the Chinese and Arabian annals with respect to the Lyrids, Perseids, and Leonids. However, the disappearance of the Leonids at the end of last century is evidence that critical changes in the conditions of seeing are possible for these showers too.

Showers produced by the other two groups exhibit far less stability as far as conditions of seeing are concerned. Thus, the most effective meteor shower of the second group was for a long time the Andromedids (otherwise called the Bielids) that exhibited rich displays in 1741, 1798, 1830, 1838, 1847, 1867 and veritable storms of shooting stars in 1872 and 1885. The meteors of the Andromedid stream move in an orbit which is very close to the orbit of Comet Biela (1852 III) with a period of about 6.5 years. These showers are connected with the break-up of Biela's comet in 1846 into two parts and the appearance of a swarm of tiny particles spread along its orbit. True, as in the case of the Perseids, Leonids, and Lyrids, the Andromedids had been observed long before the discovery of Biela's comet so that its disrupture in 1846 only enriched the meteor swarm with new material. For this reason, one should speak of an interrelationship and common origin of the Andromedids (Bielids) and of Comet 1852 III. Since 1885 the Andromedids are scarcely at all observed any more as their orbit has been altered by the strong perturbations of the major planets, primarily Jupiter, and no longer comes close to the earth's orbit.

Another meteor stream of the same group is the Draconids, or, as they are sometimes called, the Giacobinids (October 8-10). They have an orbit close to that of Comet 1946 V (Giacobini-Zinner) also with a period of about 6.5 years. The Draconids encounter the earth every 13 years and put on rich displays in 1933 and 1946; the next shower of this stream is expected in 1959. Prior to 1933 the orbit of the Draconids passed at a distance from the earth's orbit, but later began to approach it as a result of planetary perturbations.

In the second group of meteor streams are also the Bootids connected with Comet Pons-Winnecke (1951 VI) with a period of 6.15 years, the Taurids moving in an orbit close to that of Comet Encke (1954 IX) and with a period about the sun of 3.3 years, and the day-time meteor

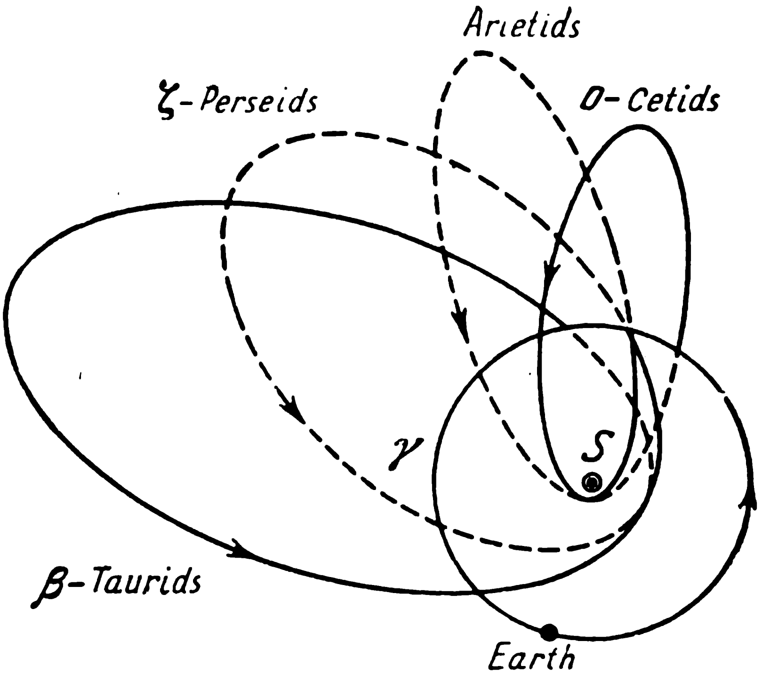


Fig. 24. Orbits of day-time meteor streams

streams observed by radar (Fig. 24). The Geminids and Quadrantids have very short-period orbits of 1.7 and 2.4 years. The Geminids are distinguished by a pronounced asymmetric structure in the cross section of the stream: prior to the date of maximum the hourly rates of meteors are regularly greater than during the corresponding time interval following this date. The Geminid radiant of diameter not over 4° has a pronounced diurnal shift, which, according to visual, photographic and radar observations, amounts to: $\Delta\alpha = +1.1°$, $\Delta\delta = -0.1°$. Of the streams of the third group, mention may also be made of the Scorpionids that frequently produce brilliant fireballs and are, apparently, related to Comet Lexell 1770 I which had a period of about five years.

In bringing to a close this survey of meteor streams, we must mention their relationships with sporadic meteors. For a long time astronomers drew a sharp dividing line between these two classes of meteors. Whereas such streams as the Perseids and Leonids were firmly established as members of the solar system as far back as the sixties of last century, sporadic meteors were regarded as a foreign element that consists of particles moving at random in all directions. Further development of such concepts led astronomers to the conclusion that sporadic meteors are interstellar in origin. However, this proved to be wrong after a closer study of meteoric phenomena. As the study both of sporadic meteors and meteor showers is pushed forward, this historically originated dividing line

between the two classes of meteoric matter is gradually being wiped away. The findings of the latest radar observations permit regarding sporadic meteors as bodies in orderly direct motion around the sun with periods on an average of about three years. This makes them similar to a very extensive class of short-period meteor streams of the second and third groups. Sporadic meteors are distinguished from shower meteors not by origin or type of orbit relative to the sun, but by the fact that they are not united in relatively compact groupings, the relationships between the component members of which are so obvious to the terrestrial observer. Again there is a specific difference in the brightness distribution of meteoroids which, apparently, is an indication of a difference in age between sporadic and shower meteors. However, these differences in the nature of the two classes of meteors are secondary. All the meteors that we observe flare up due to encounters, with the earth, of meteoroids that belong to the solar system and comprise a single huge cloud of meteoric matter in motion about the sun.

9. METEORS AND OTHER SMALL BODIES OF THE SOLAR SYSTEM

Meteors are not the only small-size bodies of the solar system. In the solar system we distinguish big bodies: the sun, planets and their larger satellites, and small bodies: meteors, the minor planets (or asteroids) and comets. All these bodies have small masses that sharply distinguish them from the major planets and the sun (Fig. 25). The asteroids (which in Greek means "starlike") revolve about the sun principally in the zone between the orbits of Mars and Jupiter. They are small solid bodies, which, like the planets, shine by the reflected light of the sun. The first asteroid was discovered by the Italian astronomer G. Piazzi on January 1, 1801, and was called Ceres. Since that time the number of asteroids dis-

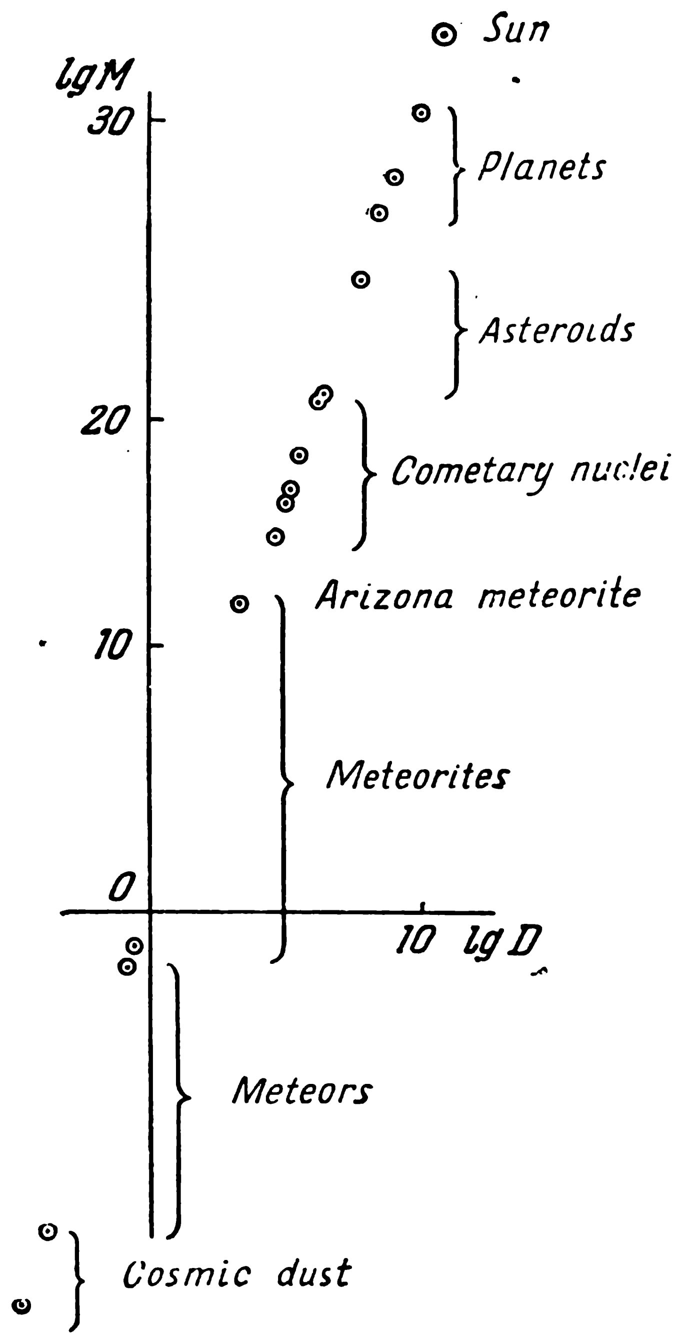


Fig. 25. Masses and dimensions of bodies of the solar system. Plotted on the horizontal scale are the logarithms of diameters, on the vertical scale—logarithms of masses in the CGS system

covered each year has been constantly mounting, and at present there are 1,615 asteroids with defined orbits, while the number of asteroids brighter than twentieth magnitude is estimated by I. Putilin to be in the neighbourhood of 140,000. Under the best of seeing conditions the brightest asteroids do not exceed sixth magnitude stars, that is to say, they are only on the boundary line of naked-eye visibility. The faintest of some recently discovered asteroids have a brightness of the seventeenth magnitude.

Only in the case of the very largest asteroids has it been possible to measure their diameters. The results are: Ceres with a diameter of 767 km., and Pallas, Juno and Vesta 489, 193 and 386 kilometres across respectively.

The sizes of the other asteroids are evaluated from their brightness. If we know the distance of an asteroid from the sun and the earth and take the albedo (reflecting power) of asteroids to be close to that of Mars, it is possible to calculate the magnitude an asteroid will have at a distance

Table 11

Diameters of Asteroids

g, magnitude	d, kilometres	g, magnitude	d, kilometres
4	581	11	23
5	367	12	15
6	231	13	9
7	146	14	6
8	92	15	4
9	58	16	2
10	37	17	1,5

of one astronomical unit from the sun and the earth (g) and therefrom estimate its diameter (d). Table 11 clearly shows how d depends on g.

Discovered in 1937, the minor planet Hermes is only some 400 m. across—something in the nature of a large crater-forming meteorite.

Asteroidal masses fall off rapidly with brightness. They may be estimated if we know the sizes of the asteroids and if we take their mean density at 3 gr./cm.^{3} N. Shtaude has calculated that the total mass of all the asteroids can hardly be expected to exceed that of Ceres by seven times. In the estimation of Fesenkov, Putilin and other workers the total mass of all asteroids is less than that of the earth by a factor of roughly 1,000, and the mass of all small, still undiscovered asteroids is probably less than four per cent of this total mass.

The brightness of many asteroids does not remain constant but experiences considerable and irregular fluctuations, which is an indication that the shapes of asteroids are irregular and that they are rapidly rotating on their axes, for in different positions they reflect different quantities of sunlight. A typical case of irregular shape

is that of Eros, which changes its brightness by as much as 1.5 magnitudes. To explain such fluctuations in the brightness of Eros, we assume that it has an elongated angular shape something like a long brick rotating about its small axis.

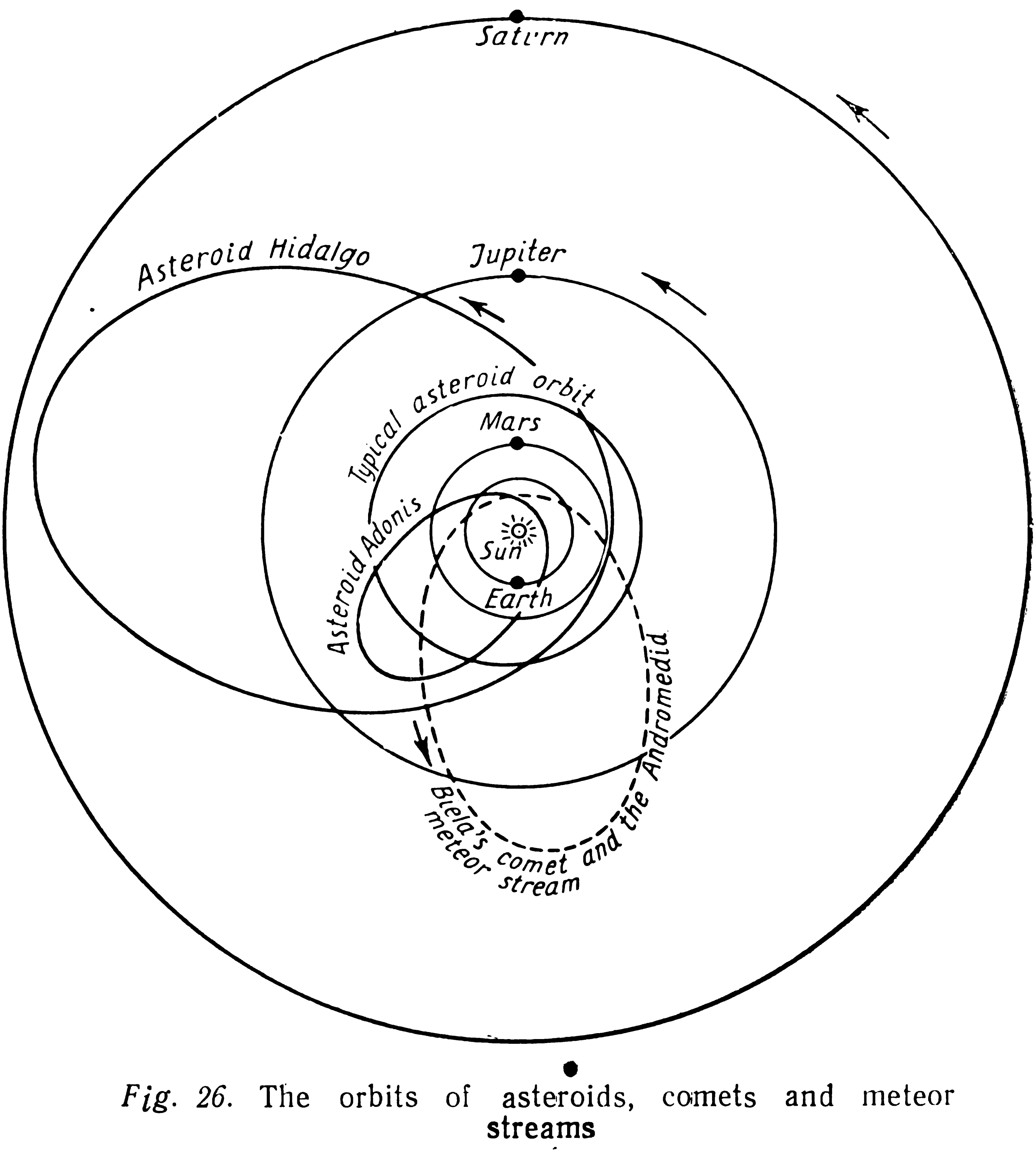


Fig. 26. The orbits of asteroids, comets and meteor streams

The albedos of asteroids can be measured directly only after the dimensions have been ascertained from observations. The albedos of the largest asteroids are as follows:

Ceres	0.10
Pallas	0.13
Juno	0.22
Vesta	0.48

The albedos of the minor planets vary through a very great range and for the first three asteroids are close to that of the moon and dark stony meteorites. The brightest of the minor planets is Vesta, which has a reflecting power similar to that of certain greyish-white meteorites. This suggests that asteroids are made up of stony material.

The asteroids have a great diversity of orbits. The majority move in the space between Mars and Jupiter in elliptical orbits that are nearly circles. Yet there are quite a few orbits in the form of elongated ellipses that swing inside the earth's orbit. Apollo, Adonis, Amor, Hermes, Ganymede and other asteroids can approach the earth at very close distances. For instance, on October 30, 1937, Hermes came within 580,000 kilometres of the earth, which is only 1.5 times the distance to the moon. The orbits of some asteroids do not at all differ from those of meteor streams or comets, as may be seen in Fig. 26.

Not excluded is the possibility of an asteroid colliding with the earth. If we recall that the masses of small asteroids are close to that of the initial mass of a large meteorite (such as the Tunguska or the Sikhote-Alin) and that their shapes are also fragmentary, as is the case with big meteoroids, we may conclude that asteroids are directly related to meteorites.

In contrast to asteroids, comets appear at first glance to belong to the largest bodies of the solar system. Cometary heads have diameters that frequently exceed that of the sun, and their tails extend out hundreds of millions of kilometres. Yet their masses are so insignificant that they rightly belong in the class of small bodies of the solar system. The main mass of a comet is concentrated in its nucleus which from earth has an almost stellar appearance. The nucleus is surrounded by a bright nebu-

lous coma, which ejects jets and fans that sweep past the nucleus in a direction opposite that of the sun. The general outline of these ejections form the shell of the comet. The nucleus of the comet together with the shell or shells form the head of the comet from which extend one or several tails. Comets grow tails when they approach the sun, but at a great distance from the sun a comet appears as a fuzzy round spot. Some comets do not produce tails even when they come close to the sun. A comet of this type consists of a head only.

The cometary head is sometimes very simple consisting only of a single starlike nucleus. The nucleus is regarded as the principal part of the comet and the source of all other phenomena observed in comets. In size, cometary nuclei are exceedingly small. For example, in May 1910, the nucleus of Halley's comet passed between the sun and the earth, but even with big telescopes it was impossible to distinguish anything on the solar disc, as was also the case when Comet 1882 II passed in front of the sun. It is estimated that the nucleus of Halley's comet was not more than 30 km. across. The French astronomer Baldet observed in a large telescope Comets 1927 VII (Pons-Winnecke) and 1930 VI (Schwassmann-Wachmann 3), which came very close to the earth, and estimated the diameters of their nuclei at roughly 400 m.

The mass of a cometary nucleus is also exceedingly small. Comet Lexell 1770 I passed in the immediate vicinity of Jupiter's satellites without causing perceptible perturbations in their movements. The same comet came within 2.4 million kilometres of the earth without affecting in any way the movements of our planet or of the moon. Hence its mass should not exceed 10^{-6} that of the earth. Vorontsov-Velyaminov estimates the mass of the nucleus of Halley's comet at 3×10^{19} grammes, or 5×10^{-9} times that of the earth.

Formerly it was thought that the nuclei of comets could consist of a cluster of fragments that resemble large me-

teoric bodies. However, the Kazan astronomer A. Dubyago showed in 1950 that such a nucleus would not be stable due to collisions of the fragments and that it would very soon become a single piece from the sticking together of the fragments. It is therefore far more probable to consider the nuclei of comets as conglomerates. In the same year, 1950, F. Whipple (U.S.A.) advanced a hypothesis, now generally recognized, of a monolithic ice-nucleus comet. On this hypothesis, the cometary nucleus is a conglomerate of meteoric materials and ices such as water, ammonia, methane, carbon dioxide, and other materials.

When the comet approaches the sun the solidified gases vaporize and form a coma, shells and tails. Due to rotation (a thing peculiar to all cosmic bodies including cometary nuclei), solar radiation will heat all sides of a comet more or less uniformly. As a result the surface of the icy nucleus becomes covered over with a thin layer of meteoric dust, which is a poor conductor of solar heat. This prevents the volatile substances in the cometary nucleus from evaporating rapidly. The ejection of gases from the head of the comet is a source of reactive forces that act on the cometary nucleus, which fact, according to Dubyago, serves as a good explanation of secular decelerations or accelerations in the movement of certain comets, as for instance, Comets Encke, d'Arrest, or Wolf (1).

Cometary orbits fall into two large classes. The first class embraces the extremely elongated ellipses that differ but slightly from parabolas. To simplify calculations in this case, the movement of a comet in such an orbit is taken to be that of a parabola. Long period is the name given to such comets. A typical long-period comet is Halley's with its period of 76 years. The aphelion of its orbit is situated out beyond the orbit of Neptune. It will be recalled that the same orbits were found for Type I meteor streams, some of which move in the orbits of long-period comets that correspond to them.

The second class of cometary orbits are short-period elliptical orbits with aphelia close to the orbit of Jupiter. Some of these orbits (Comets Encke and Wilson-Harrington) are completely inside the Jovian orbit. Short-period comets have periods ranging from 2.3 to 17.9 years. Among them we encounter nearly circular orbits (Comets Schwassmann-Wachmann 1 and Oterma) which, in effect, do not differ from the asteroidal orbits. Type II meteor streams and some of Type III have orbits similar to those of short-period comets. Some of these streams move in orbits that are exceedingly close to the orbits of such comets as Encke, Biela, Pons-Winnecke, and others.

At present we know the orbits of 525 comets, which number may be broken down as follows: due to a lack of proper observations, approximate parabolic orbits have been computed for 274 comets, in the case of 52 comets the orbits are hyperbolic, and for 199 they are elliptical. Of the comets with elliptical orbits, 114 have periods in excess of 200 years, that is to say, they are long-period comets. Since the movement of comets along hyperbolas is usually due to perturbations caused by the giant planets, especially Jupiter and Saturn, and the initial orbits of such comets are also extremely elongated ellipses, the conclusion should be drawn that 440 comets (nearly 84 per cent of the total number) have highly elongated long-period orbits.

This predominance of long-period orbits is still more overwhelming if we take into consideration the seeing conditions of both classes of comets. Short-period comets move close to the sun approaching the earth repeatedly. Under the action of solar rays, the short-period comets glow more brilliantly and develop gaseous tails that are easily seen at a comparatively small distance from the earth, whereas the long-period comets spend most of their time far from the sun and the earth out of the range of terrestrial observers. For this reason the number of long-period comets that belong to the solar system and that

accompany the sun in its motion relative to the stars should be very great.

The Dutch astronomer J. Oort suggested in 1950 that the cloud of comets round the sun extends out to a distance of roughly 200,000 astronomical units, that is, it has a diameter comparable to the distance to the closest stars. This cloud fills the entire sphere of the sun's gravitational field—that part of space in which solar gravitation exceeds that of the neighbouring stars. The number of comets in this cloud comes to 10^{11} so that the total mass of cometary material in the solar system is probably close to 100 earth masses, or 10^{-3}-10^{-4} times the mass of the entire solar system.

Due to perturbations caused by the attraction of close stars, the comets one by one move into the inner regions of the cloud. Here they describe highly elongated elliptical, nearly parabolic, trajectories relative to the sun. The attraction of the giant planets can impart an additional acceleration to a comet that appears in the inner regions of the solar system, and as a result the comet will be thrown out of the solar system along a hyperbolic orbit. In other cases the perturbations of the giant planets retard the motion of the comet so that it moves into the inner regions of the planetary system. Some of the comets have been captured by Jupiter to form a relatively small group of short-period comets that are easily seen from the earth. The accumulation of comets in the outer regions of the solar system is a sort of storehouse or "refrigerator," where the comets exist an unlimited long time until stellar perturbations force them closer to the sun. It is then that the last stage in the life of the comet sets in. As it moves into the environs of the sun the action of solar radiation begins to destroy the comet rapidly making it lose its light volatile gases. The frozen gases evaporate giving birth to magnificent tails; during very close approaches to the sun the heat is so intense that it evaporates from the cometary nucleus not only ices, but also

such refractory elements as sodium, calcium, and even iron. In each revolution about the sun the comet leaves behind some of its material. No wonder then that the short-period comets, which are forced to stay for long periods of time under the destructive action of solar rays, rapidly lose material and perceptibly diminish in brightness during very short intervals reckoned in decades, as was first detected by the Soviet astronomer S. Vsekhsvyatsky.

Remarkable investigations into the nature of comets and the character of their gradual disintegration were carried out in the latter part of the nineteenth century by the noted Russian astronomer F. Bredikhin. Working from the concept that particles ejected from the cometary nucleus are acted upon by two forces: solar gravitation and a repulsive force of solar origin, Bredikhin showed that the great diversity of cometary tails could be reduced to three basic types. The tails of Type I (Fig. 27) are the nearly rectilinear tails that extend almost directly away from the sun. The repulsive forces in Type I tails are very considerable and exceed by a factor of 20-1,000 the forces of solar attraction. The tails of Type I are gaseous being made up of the ionized molecules of nitrogen and carbon monoxide. The repulsive solar forces acting on the curved broad tails of Type II are weaker (0.6 to 2.2 times that of solar attraction). These forces are still weaker in the short tails of Type III which are deviated almost exactly in the direction opposite the movement of the comet.

The nature of the repulsive force is clear only for the tails of Types II and III: it is the pressure of solar radiation. The forces operative in Type I tails are so great that something more than light pressure must be invoked to explain them.

S. Orlov, prominent Soviet investigator of comets, believed that tails of Types II and III consist of minute dust particles ejected by the cometary nucleus possibly as a

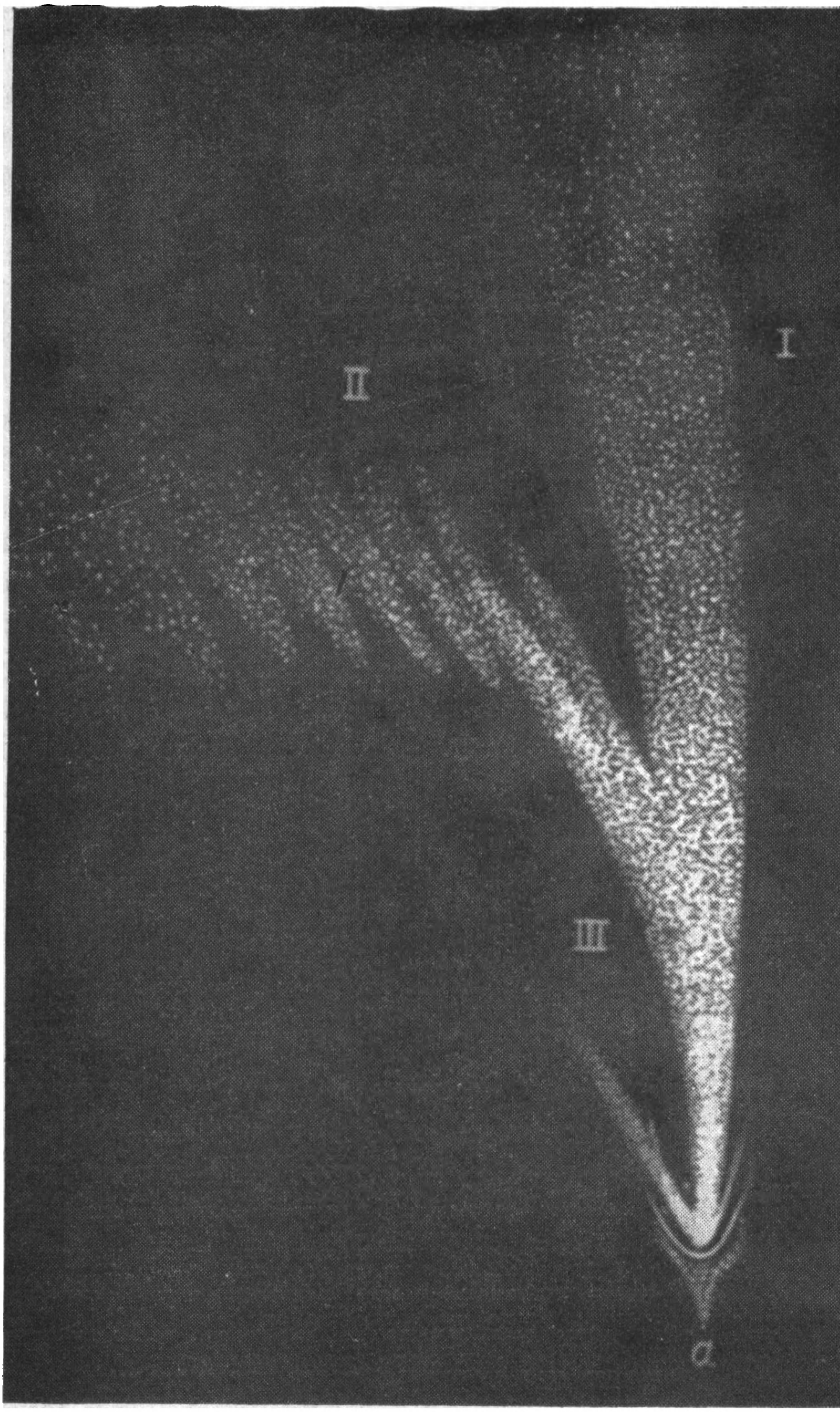


Fig. 27. Types of cometary tails in Comet 1910 I
(*a*—a short anomalous tail)

result of collisions of the nucleus with meteoroids. B. Levin considers that Type II tails are not of the dust type, but consist (like those of Type I) of gases, carbon and cyanogen. However, even if Type II tails consist of dust particles they must be exceedingly small, of the order of 10^{-5} cm. (fractions of a micron), which is to say that the matter of these tails is in a far more disintegrated state than meteoric matter.

Only the anomalous cometary tails discovered and studied by Bredikhin consist of larger particles over 0.01 mm. across. According to Bredikhin these anomalous tails (Fig. 27, *a*) are a result of the ejection of disintegrated meteoric matter from cometary nuclei. They are formed when comets approach the sun. Though anomalous tails are rather infrequently observed (when the jet of ejected particles is sufficiently dense), such ejections are apparently a common phenomenon in the course of the gradual disruption of comets. The cause of the ejection may be a sudden surge of heated gas from the inside of the cometary nucleus that entrains solid particles, or a collision of the nucleus with a large asteroidal-type meteoroid, or, finally, it may be the tidal action of the sun.

The important thing is that the initial velocity and direction of the ejection can vary over a great range of values. If its initial velocity is not great, for instance, in the case of the action of tidal forces, the orbits of the ejected particles will differ but slightly from the original orbit of the comet. But if the speeds of ejection are relatively high, the orbits of the incipient meteor streams can differ greatly from the original orbit of the comet. In this case, only the intersection of the orbits of the comet and the meteor stream at the point of ejection will indicate a connection between the meteors and the comet.

We thus see that Bredikhin establishes more complex and general characteristics in the interrelationships between the parent comet and the meteor stream than a sim-

ple coincidence of orbits. The complex structure of the Perseids, where in addition to the central radiant we find a large number of side branches of the stream, confirms the view taken by Bredikhin. True, the visual observation materials used by Bredikhin are encumbered by considerable accidental errors that lead to a scattering of the radiants over the sky. But a study, carried out in 1954 by Babadzhanov under the guidance of Orlov, of photographs of the Perseids obtained in Stalinabad confirms the correctness of Bredikhin's conclusions. To explain meteor orbits deviating from the orbit of the central branch of the Perseids, we must assume ejections from the nucleus of Comet 1862 III with initial velocities of 2 to 3 km./sec.

The Czech astronomer M. Plavec gives considerably smaller speeds (of the order of 10 m./sec.) for ejection in the Draconids. He says that if the meteor cloud is ejected from the cometary nucleus at an initial speed of 0.01 km./sec. in a forward direction, the following time periods will be required for the cloud to overtake the parent comet by one half an orbit:

Stream	*Number of circuits*
Geminids	96
Draconids	108
Leonids	35
Orionids	15
Lyrids	6
Aurigids	2

Whatever the process of gradual disintegration of the comet, it leads to the separation of an independent agglomerate of meteoric material, that is, to the formation of a meteor stream. The orbit of this stream can remain very close to the orbit of the parent comet or it can differ appreciably. Thus, there exists an intimate genetic relationship between comets and meteoric streams. This relation-

ship was suspected a long time ago by nineteenth century astronomers on the basis of the simple but very important fact of coinciding orbits of certain meteor streams and comets.

We now consider the nature of the zodiacal light, a phenomenon which, in the opinion of a number of authorities, including Fesenkov, is to be explained by the reflection and scattering of sunlight by minute particles of meteoric dust. The zodiacal light is observed in the form of bright cones (after sunset or just before sunrise) that extend along the ecliptic, that is, near the plane of the earth's orbit. The zodiacal light is especially bright on dark nights in the southern latitudes where the ecliptic is high above the horizon. Here it is sometimes possible to see both cones of light join to form a single band. In the area opposite the sun there is observed a bright spot, the so-called counterglow.

Up until recently there were two views concerning the nature of the zodiacal light. One was that it is caused by a bulging of the terrestrial atmosphere along the equator. Illuminated by the sun and even the moon, these distant regions of the atmosphere are seen as the zodiacal light and the counterglow. The other view was that the zodiacal light could be fully explained by a lens-shaped cloud of dust-like meteoric matter around the sun that scatters the sun's rays.

Investigations in recent years, chiefly by the Soviet scientists Astapovich, Divari, Fesenkov, and Tikhov, have shown that the zodiacal light is a complex phenomenon produced both by the glow of distant regions of the terrestrial atmosphere and by the scattering of the sun's rays in the cloud of free electrons and fine meteoric dust that surrounds the sun. The counterglow has proven to be a gaseous tail of the earth facing the side opposite the sun.

Thus it was that Lomonosov's brilliant conjecture made in the eighteenth century was confirmed. Lomonosov's idea

was that the earth, like comets, has a tail made up of tenuous glowing gases of the air and visible from the moon. He got it from a parallel which he drew between cometary tails and the aurorae. Studies of the spectrum of the zodiacal light confirmed the gaseous nature of the phenomenon as a whole. It was found that an exceedingly rarefied terrestrial atmosphere extends out several thousand kilometres along the plane of the earth's equator in the form of a lens. The faint glow of this atmospheric lens of the earth uncluding its tail directed away from the sun is what comprises the first, gaseous, terrestrial component of the zodiacal light.

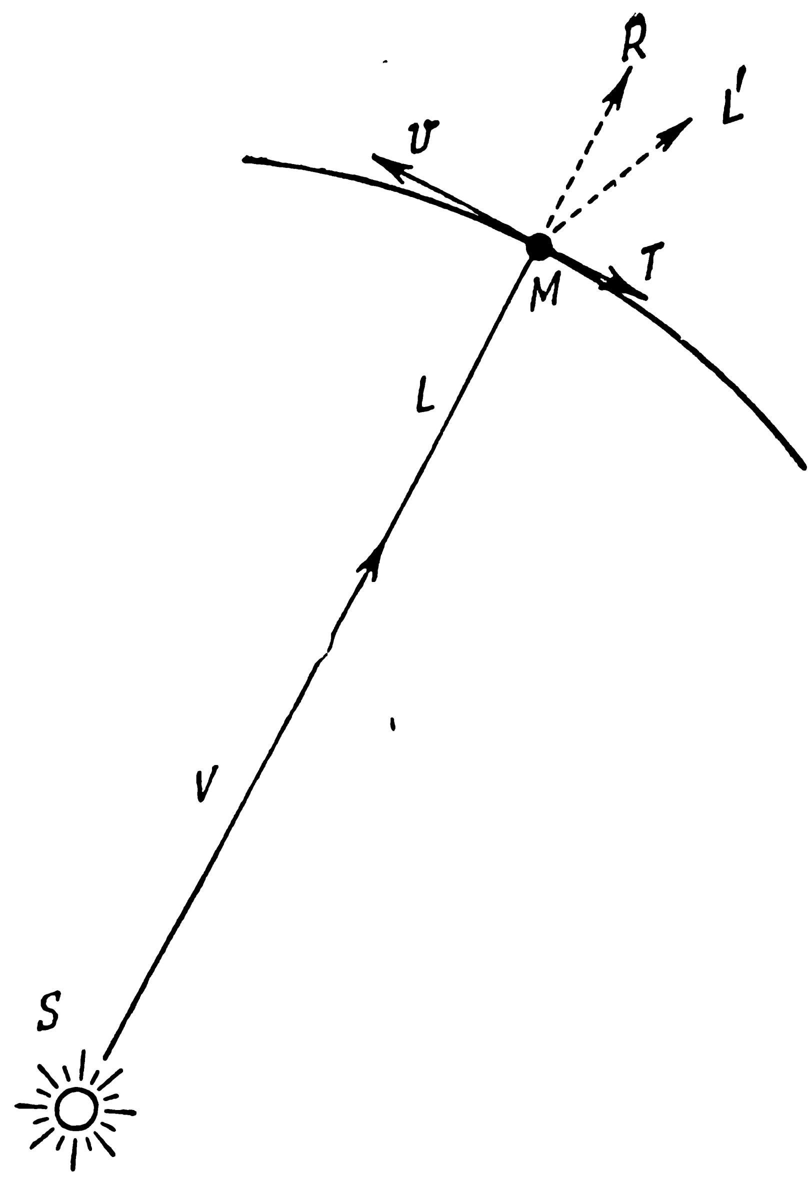


Fig. 28. The action of light pressure on a particle *(M)* revolving about the sun *(S)*. Due to composition of the velocity of light *(V)* and the orbital velocity of the particle *(v)*, the ray of light *(L)* is directed, relative to the particle towards *L'*, thus creating a radial repulsive pressure *(P)* and a tangential decelerating pressure *(T)*

The second part of the zodiacal light is made of sunlight scattered by a cloud of electrons and minute particles of meteoric dust in the form of a lens-shaped concentration about the sun. The effect of radiation pressure—the so-called Poynting-Robertson effect—on these tiny dust particles should be very noticeable. Let us visualize a particle illuminated by the sun's rays (Fig. 28). Due to the

composition of velocities of light and the orbital motion of the particle, the light pressure will be slightly opposed to the motion of the particle. It will therefore retard the orbital motion of the particle. Due to the decelerating action of the light pressure, the particle will spiral inwards towards the sun and finally fall on to it. The smaller the mass of the particle the greater will the retarding action of solar radiation be and the sooner it will fall on to the sun. The Poynting-Robertson effect is made still stronger by the action of corpuscular solar radiation. Due to the joint action of these two factors, the sun sweeps up every second not less (probably much more) than a ton of dust material. Consequently, the dust cloud about the sun must be constantly replenished, and in order to maintain the existence of the zodiacal light several tons of meteoric material are required every second. This material is probably supplied chiefly as a result of the disruption of meteoroids in collisions. The meteoric cloud about the sun consists of particles of size from 1 to 300 microns that extend out to a tremendous distance, even beyond the orbit of the earth. The reflection of sunlight from this constantly renewing cloud is the second component of the zodiacal light. Thus we establish a relationship between the zodiacal light and the smallest meteoric particles.

We see that the asteroids, comets and, in part, the zodiacal light are intimately related to meteors. Meteoric matter is a component part of the assemblage of small bodies of the solar system; a product of the disintegration of larger bodies, it passes into other, still more pulverized types of matter, as, for example, the cloud material of the zodiacal light.

Having examined the relationship that exists between meteoric matter and the other small bodies of the solar system, let us now survey the processes of evolution of these bodies.

10. PROCESSES OF EVOLUTION IN THE SYSTEM OF SMALL BODIES OF THE SOLAR SYSTEM

We first consider the principal factors that affect the small bodies of the solar system. These are gravitational perturbations produced by the major planets, tidal action of the sun, the effect of radiative and corpuscular pressure, the influence of thermal solar radiation, collisions of particles, and, finally, reactive eruptive forces. Each of these factors produces a specific effect on the small bodies of the solar system. Their action differs under different conditions.

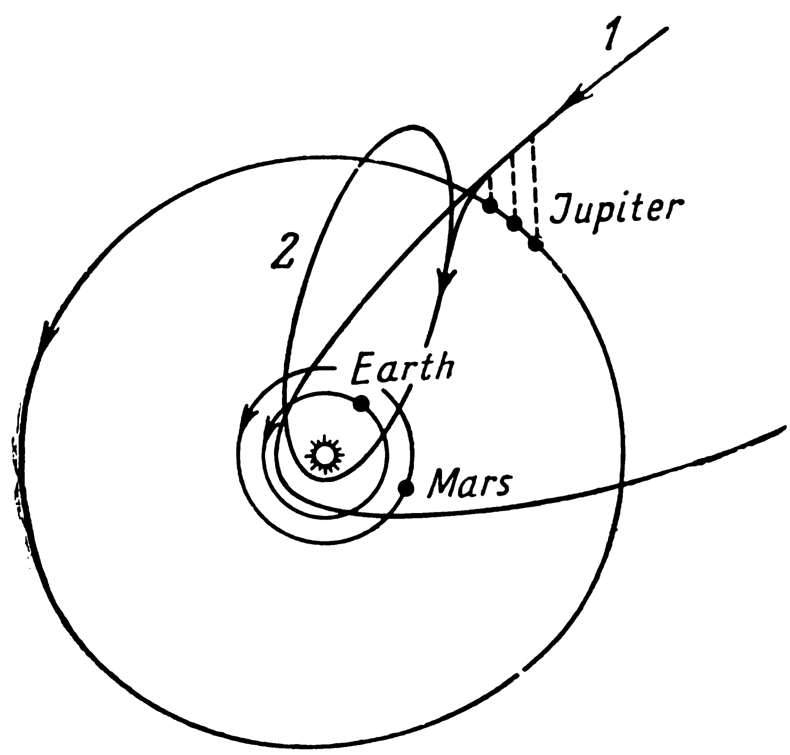


Fig. 29. Jupiter changes the orbit of a comet. *1*—the original orbit, *2*—the altered orbit

The gravitational perturbations of the major planets, particularly Jupiter and Saturn, alter the orbits of the small bodies (Fig. 29). It has already been mentioned above that the perturbations of Jupiter are capable of changing long-period closed orbits into elliptical short-period orbits or, on the contrary, into hyperbolic orbits. It was precisely in this way that the family of comets and meteoric streams of the Jovian group were formed.

However, this is not all that Jupiter is capable of doing to the assemblage of small bodies close to its orbit. Small bodies (asteroids, meteors) with periods that are multiples of that of Jupiter, or are related to the latter as rational fractions (for example, 1/3, 2/5, 3/7, 1/2, etc.) will be subject to particularly frequent and strong gravitational perturbations by Jupiter and will inevitably be thrown into other, nearby, orbits that

are more stable. As a result, in the group of small bodies, that have similar periods and orbits there appear small breaks known as gaps. Similar gaps are clearly visible in the rings of Saturn, which, as was established

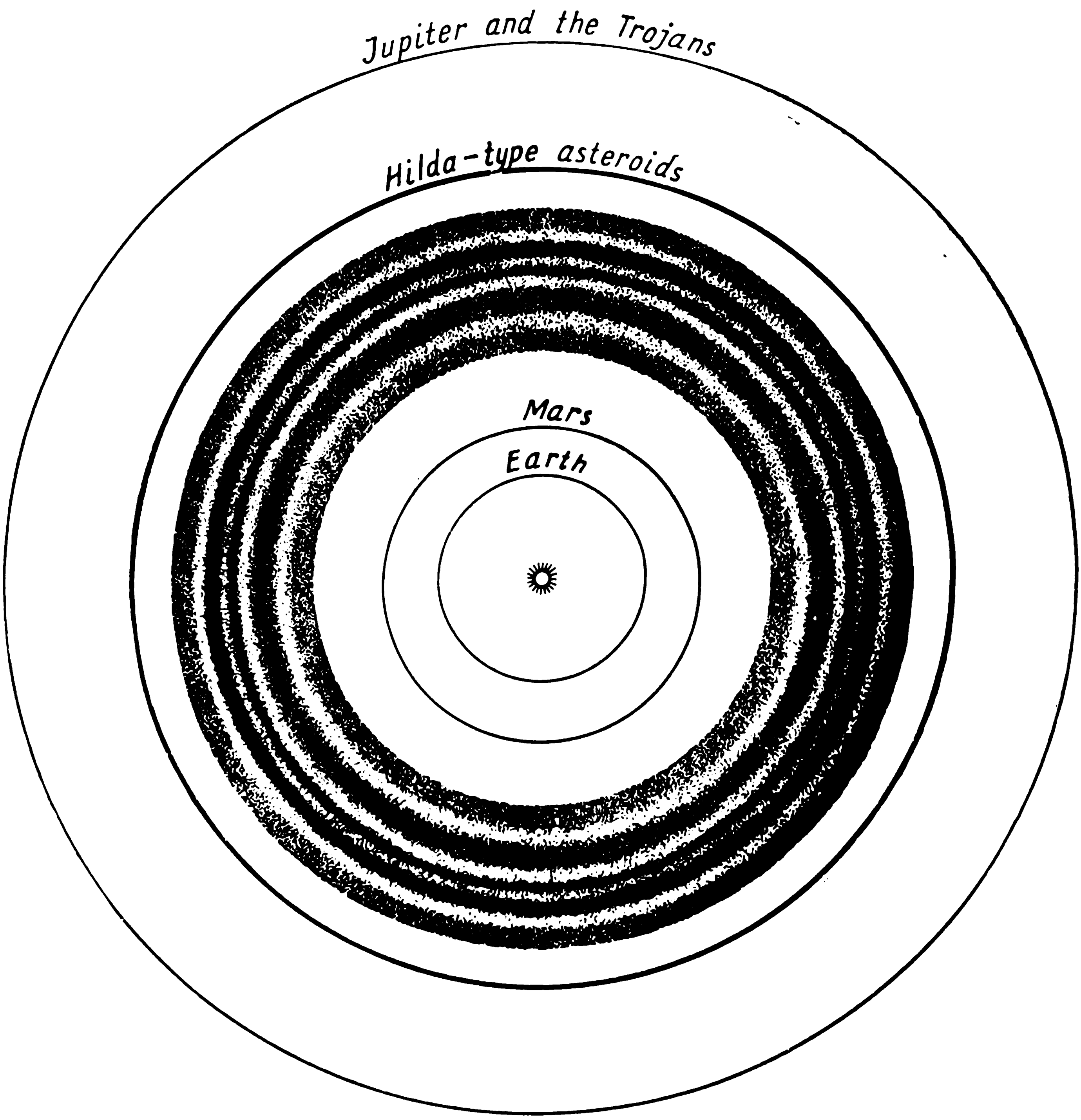


Fig. 30. The asteroidal belt in plan

as far back as the end of last century by the Russian scientists S. Kovalevskaya and A. Belopolsky, consist of tiny meteoric bodies. In Saturn's rings these gaps are produced by perturbations of the planet's satellites. The

gaps in the group of asteroids may be seen on the diagram of their distribution according to distance from the sun (Fig. 30). This is a peculiar type of dynamic resonance in a cloud of small bodies due to a periodically acting gravitational force.

Further, stable groups of small bodies that accompany Jupiter in its journey about the sun are formed in the vertices of equilateral triangles (the other two angles of which are occupied by the sun and Jupiter), that is, at so-called libration points 60° ahead of or behind Jupiter in its orbit. This is the Trojan group of asteroids that bear the names of heroes of the Trojan war. Similar points of libration, around which fragmentary and dust material concentrate, are found on the continuation of a straight line connecting the sun with any one of the major planets. Thus, the joint gravitational action of the sun and the planets lead to the formation of inhomogeneities in the spatial distribution of dust and fragmentary material in the solar system.

If such small bodies as cometary nuclei or swarms of meteoroids come close enough to the sun they experience tidal forces. It is known that tidal forces arise as the difference of gravitational forces acting on a body, the size of which is comparable to the distance between the attracting bodies. Tidal forces (F) are directly proportional to the mass (M) and inversely proportional to the cube of the distance between the bodies (R), so that $F = K\frac{M}{R^3}$. Due to the fact that tidal forces fall off rapidly with distance, they are effective only at small distances from the perturbing body. This, among other things, is why the magnitude of a lunar tidal wave in the oceans of the earth is over twice that of a tidal wave produced by the action of the sun. The tidal forces of the sun produce considerable perturbations in the meteor streams passing close to it and appreciably alter the orbits of separate fragments. The small initial differences in the orbits of bodies at perihelion result in far greater dispersal at remote distances

from the sun. Thus, the action of a solar tide amounts to the scattering of the original compact beam of orbits. And what is more, due to changes in the periods of the different particles the whole swarm of meteors gradually spreads itself along the orbit. The older the meteor stream and the more times it has passed the sun the more evenly will the material be spread along its orbit. Such is the action of the solar tidal forces on the structure of a meteor swarm as first described by Schiaparelli.

The relatively larger compact bodies such as asteroids or stony nuclei are not affected by tidal forces until the latter exceed the force of internal cohesion of the particles of the body. The limit distance at which tidal forces exceed the forces of internal cohesion of a liquid (or loose) body is known as the Roche limit. For planets the Roche limit is a critical distance below which the formation of satellites of the given planets could not proceed. We may visualize the meteoric rings of Saturn with their innumerable tiny particles, as having originated just this way, a sort of "abortive" satellite.

The tidal forces that act on comets and meteors are not all due to the sun, the planets likewise produce such forces, but they are much smaller corresponding to the difference in the mass of the planet and the sun. Thus we see that the action of tidal forces amounts to a break-up of assemblages of meteoroids and even of individual large-size solid bodies.

We have already spoken about solar radiation (light waves and corpuscles) that produces the Poynting-Robertson effect when we considered the structure of the cloud of zodiacal light. The retarding action of radiation pressure not only forces the cloud of sporadic meteoric particles to settle down slowly on to the sun, but also produces its effect on the make-up of meteor streams. Radiation pressure from the sun winnows out of the original meteor streams the smallest particles, making them spiral into the sun. For this reason the number of faint meteors

in certain periodic showers is perceptibly diminished. Particularly strong is the sweeping-up action of the Poynting-Robertson effect when meteor streams pass through perihelion. The action of light pressure is especially effective against separate gas molecules in cometary tails and dust particles of size less than one micron (that is, with diameters of the order of a wavelength of light), which are thrown out of the solar system along hyperbolas. Thus, gases and minute dust particles that form within the solar system are constantly being thrown out into interstellar space by light pressure, while inside the solar system we find particles being sorted according to size depending on the distance and frequency with which the meteor swarms approach the sun.

The heating effect of the sun on cometary nuclei, asteroids, and meteoroids leads to ablation of frozen gases from these bodies. Nearer the sun, first fusible and then refractory elements are vaporized. What occurs is a gradual modification of chemical composition and, hence, of the nature of the small bodies of the solar system.

Numerous collisions of the smaller bodies among themselves and with the planets and their satellites are highly probable due to the fact that there are so many of them in the solar system, especially in the inner regions. A typical illustration of the collision of a small body with a planet is that which produces meteor phenomena observed on the earth. This question has already been dealt with in detail. For planets protected by a more or less dense atmosphere, as for example Venus or the giant planets of the Jupiter group with their ammonia-methane atmospheres, the principal type of interaction with meteors occurs in the atmosphere of the planet. On such planets the atmosphere is always a shield that vaporizes and destroys the great majority of these meteoric bodies.

Quite different is the interaction between meteoroids and planets or satellites that are poorly protected if at all by an atmosphere, as, for instance, the Moon or Mercury.

The impact of meteoroids on the surface of such bodies with an energy that appreciably exceeds that of the internal bonds of a solid body, instantaneously converts both the meteoroid and a large volume of rock on the surface of the planet or satellite into compressed gas producing an explosion. Due to meteoric bombardment and the explosive action of meteoritic impacts, such planets and satellites lose irretrievably a part of the material thrown out in the explosion, since it acquires a speed greater than escape velocity permitting it to fly out into interplanetary space. Such meteoric bombardments act as an external (exogenetic) force in shaping the crust of the planet or satellite.

Interplanetary space is constantly being replenished with meteoric dust in the form of pulverized material ejected from the surfaces of airless bodies that gradually become covered with a thick layer of dust.

A similar but relatively more destructive effect is produced by meteoritic impacts on asteroids and cometary nuclei. S. Orlov recently pointed to the important role of meteoric bombardment in various processes in comets. For example, Comet Holmes (1892 III) exhibited a very faint tail and several dust haloes of tremendous size. The most natural explanation of these haloes is a collision of the nucleus of the comet with meteoroids. And in general the appearance of haloes around cometary nuclei may be put down to meteoric bombardment. The ejection of jets of meteoric matter from cometary nuclei at low initial speeds (several kilometres per second or even less) can likewise be produced in collisions of large-size meteoroids and comets.

In addition to such irreversible processes as disruption of the crystal lattice of the solid body, evaporation, heating and ionization, collisions of small bodies in the solar system result in elastic interaction. The processes of elastic interaction lead to an averaging of the speeds of small bodies and tend to bring the movements of the en-

tire assemblage of meteoric matter of the solar system into a single direction of motion in nearly circular orbits. A very specific role is played by collisions of small bodies in the outer regions of the solar system where relative speeds are very small. The small energies of the colliding particles not only lead to an averaging of velocities but also to sticking together of particles to form big-size chunks of material. Thus, whereas collisions of solid particles in the inner regions of the solar system results in the breaking up of solid bodies, the result at remote distances from the sun may be just the opposite—the concentration of material in certain regions of space.

All the foregoing factors are external as regards the small bodies of the solar system. It is hard to expect that these bodies are capable of displaying internal forces that might affect their development. Probably the only exception is the reactive effect that arises in the ejection of gases from cometary nuclei. The result is either acceleration or, on the contrary, deceleration of the comet in its orbit around the sun. But in this case too, the energy required to expand the gases in cometary nuclei is obtained from outside, through the absorption of the sun's radiant energy.

Such are the diverse factors that determine the development of the small bodies of the solar system. What, in rough outline, is the possible picture of the origin and evolution of the assemblage of small bodies under the action of these factors?

Undoubtedly, the principal and predominant evolutionary processes of this assemblage in the inner regions of the solar system at present are disintegration and destruction of fragmentary material that comprises the small bodies—asteroids, comets, meteor streams. Asteroids are shattered in collisions with one another and with meteoroids. The results of collisions reduce the total mass of asteroids, and at the same time increase the mass of the meteor cloud about the sun. The same is the case for the

planets and their satellites that lack atmospheric protection.

Cometary nuclei eject gases and lose minute dust particles which during explosions form whole clouds ("synchrones") often observed in the tails of comets. Comets that pass perihelion very close to the sun may have their nuclei disrupted and perish under the action of the solar tidal force. Particles of the cometary nucleus that lose all connection with the nucleus and with each other when ejected from the nucleus due to gas explosions, impacts of colliding meteoroids and the influence of tidal forces, produce meteor streams. A portion of them moves almost in the same orbit as the parent comet while the other part noticeably deviates from this orbit due to the considerable initial ejection velocities. The meteor swarm is subjected to the destructive action of planetary perturbations and tidal forces, and gradually the cluster of orbits of the meteor stream is dispersed in space, and the meteoric matter gets spread out along the orbits forming a ring around the sun. Light pressure from the sun sorts out the particles, pushing the gas molecules and very small dust particles out into interstellar space and pulling in the meteoric matter on to the sun.

This is the way the meteoric cloud in the inner regions of the solar system forms, is sorted out into a more or less compact scattered swarm moving round the sun, and is gradually destroyed. Fesenkov estimates that the meteoric matter in the environs of the sun should have been renewed many times during the 4 to 5 thousand million years that our planetary system has been in existence. As for comets, we find that their total mass diminishes in time and provides material to renew the supply of meteoric matter being destroyed. The theory of a cometary "refrigerator" whose big supply accompanies the sun explains the great profusion of comets even though they are constantly being destroyed in the vicinity of the sun.

The processes which we have just discussed characterize only the evolutionary trend of the system of small bodies at the present time and in a limited region near the sun. But a number of questions arise in connection with the earlier evolution of the small bodies. How did the comets and asteroids originate? What connection is there between asteroids, meteorites and the smaller meteoroids? Did meteoric matter exist during the formation of the solar system or did it appear as a result of the disruption of comets and asteroids? What is the evolutionary trend of small bodies in the outer regions of the solar system?

At present, only very approximate answers can be given to these queries. To draw in detail the picture of the origin and evolution of the solar system including its assemblage of small bodies will require the persistent and intensive labours of scientists over a long period of time. But a few suggestions may be made by way of refining the statement of the problem.

The origin of asteroids and comets undoubtedly goes back to the time of the formation of the solar system and was essentially different for these two classes of bodies. The cometary cloud that extends out to the gravitational fields of the closest stars appears to be a very natural remnant that took shape following the concentration, into a star, of the material of the gaseous-dust nebula.

Gradually, in the course of numerous collisions at small relative speeds, there took shape in these remote regions of the solar system numerous conglomerates of minute mass. It was these conglomerates made up of solid particles and frozen ices that became the nuclei of comets. It may be that this process of comet formation is continuing at the present time. From the "refrigerator" the comets one by one entered the inner regions of the solar system, took on short-period orbits and disintegrated giving birth to the numerous meteor streams. This means that the short-period comets and their relat-

ed meteor streams represent a relatively short-lived phase in the development of cometary-meteoric matter. If the origin of the cometary cloud is placed at 4 to 5 thousand million years ago, the ages of the now observed meteor streams may be estimated at several tens of thousands of years, or less by a factor of tens and hundreds of thousands.

Turning to asteroids, we find that their small inclinations to the ecliptic, the circular character of their orbits, the relatively large sizes of the larger asteroidal bodies, and also the position of a belt of asteroids between the orbits of Mars and Jupiter all speak in favour of a common origin of the asteroids and the planets. Most likely this was a "luckless" planet whose material was either never got together or was broken apart at some stage in the life of the planet. This latter idea is close to the hypothesis advanced by Olbers who, as early as the beginning of the nineteenth century, visualized asteroids as fragments of a large-size planet that exploded in between the orbits of Mars and Jupiter.

Asteroids extend over a tremendous range of sizes. The largest is 767 km. across while the smallest according to present, very incomplete, data have diameters of the order of 400 metres. Compare this with the largest-size crater-forming meteorites which are estimated at several tens of metres across. There is no sharp dividing line between the masses and sizes of large meteorites and small asteroids. This seems to justify Fesenkov's suggestion that the Sikhote-Alin meteorite was a tiny asteroid that collided with the earth. At the moon's distance this asteroid would appear as a sixteenth magnitude star and would be detected by powerful telescopes. It is very natural to assume that in the formation of the belt of asteroids there could arise fragments of all manner of sizes. A possible conclusion, therefore, is that large-size meteoroids have a common origin with the asteroids.

At the same time, it is obvious that the meteoroids of streams that resulted from the break-up of comets originated quite differently. The absence of large meteor bodies in streams—this is confirmed by the fact that no meteorites are found during heavy meteor showers—is evidence for a different origin of meteoroids of unlike size. However, among the meteors of cometary origin there are undoubtedly relatively large bodies as is evidenced by the brilliant fireballs originating in the Scorpionid and Taurid showers, which are related to comets Lexell and Encke. Due to a lack of sufficient material on the orbits of meteoroids, the problem of their origin still awaits a definitive solution. Unfortunately, data on meteorite orbits is exceedingly slow in accumulating. And the similarity in chemical composition of meteorites and smaller meteoroids has been established only in the most general form due to the paucity of spectral observations of meteors. We may assert that the chemical composition of shower meteors and meteorites is roughly the same, that the meteors of streams like the Perseids are, by composition, very close to stony meteorites. However, available data does not permit us to place shower meteors in a definite class of stony meteorites.

We see that there are still many gaps in our knowledge of the origin and evolution of small bodies of the solar system. But if compared with the situation some 20 years ago, we cannot but remark upon the considerable progress that has been made as a result of the successes of meteor astronomy. As in all fields of human knowledge, our understanding has broadened and we are much closer to the truth.

11. DUST IN INTERSTELLAR SPACE

The absorption of light in interstellar space indicates that the latter is filled with dark opaque matter. Such, for example, is the Coal-Sack in the Milky Way which

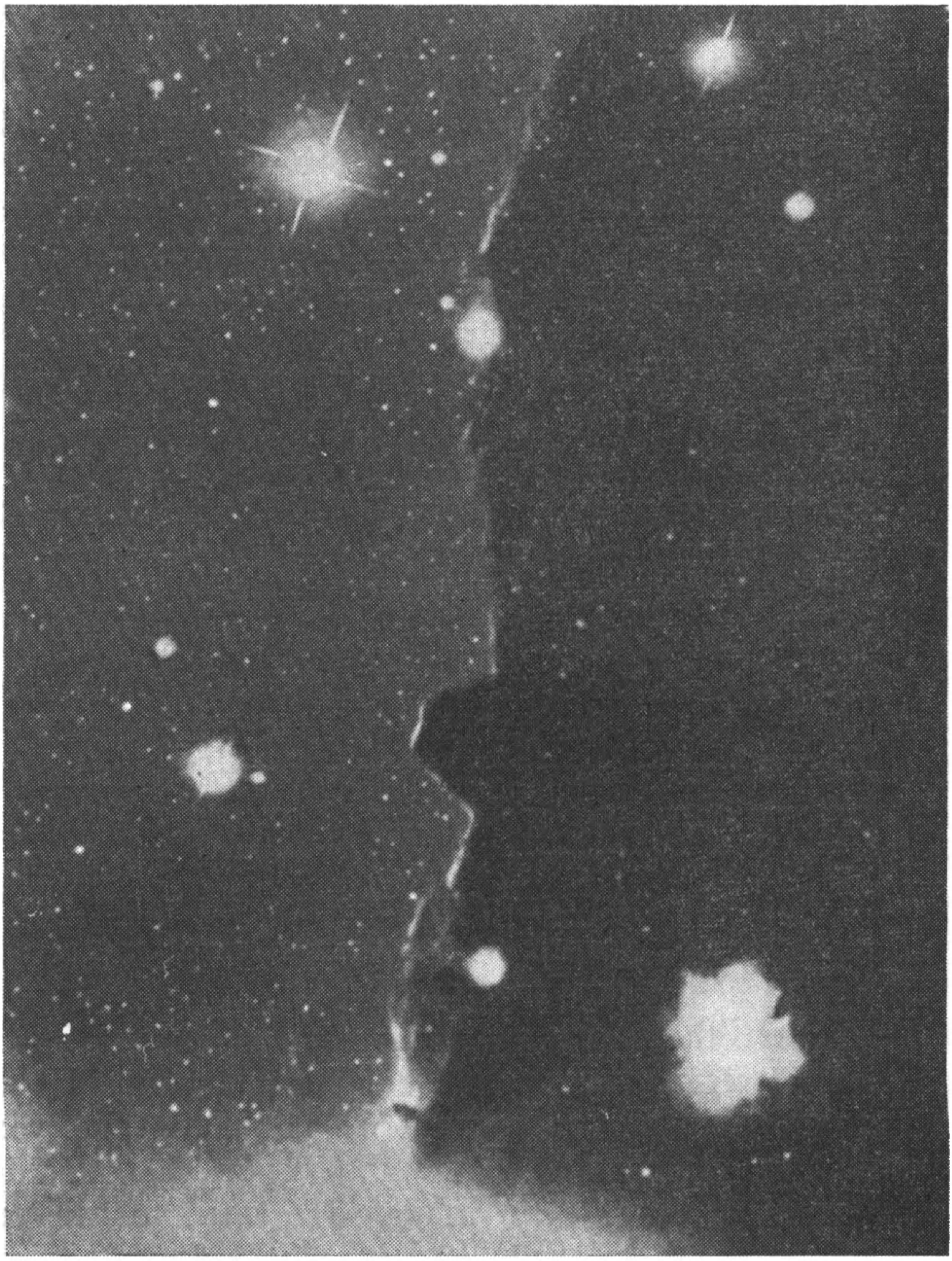


Fig. 31. The dark dust (Horsehead) nebula in the constellation of Orion

is even visible to the naked eye. This opaque matter appears in the form of a curtain easily detected in the gaseous-dust nebulae in the constellations of Orion, Cygnus, and many others (Fig. 31). The existence in interstellar space of dust matter in quantities that appreciably

exceed $^1/_{1,000}$ of the entire mass of the Galaxy, or 150 million solar masses, is at present generally recognized.

How is this dust matter related to the meteoric matter of the solar system? What role does it play in the Galaxy? We may visualize dust particles as having always existed in our stellar universe and as being just as integral a part of the Galaxy as luminous matter—the stars and nebulae. This dust participates in the develop-

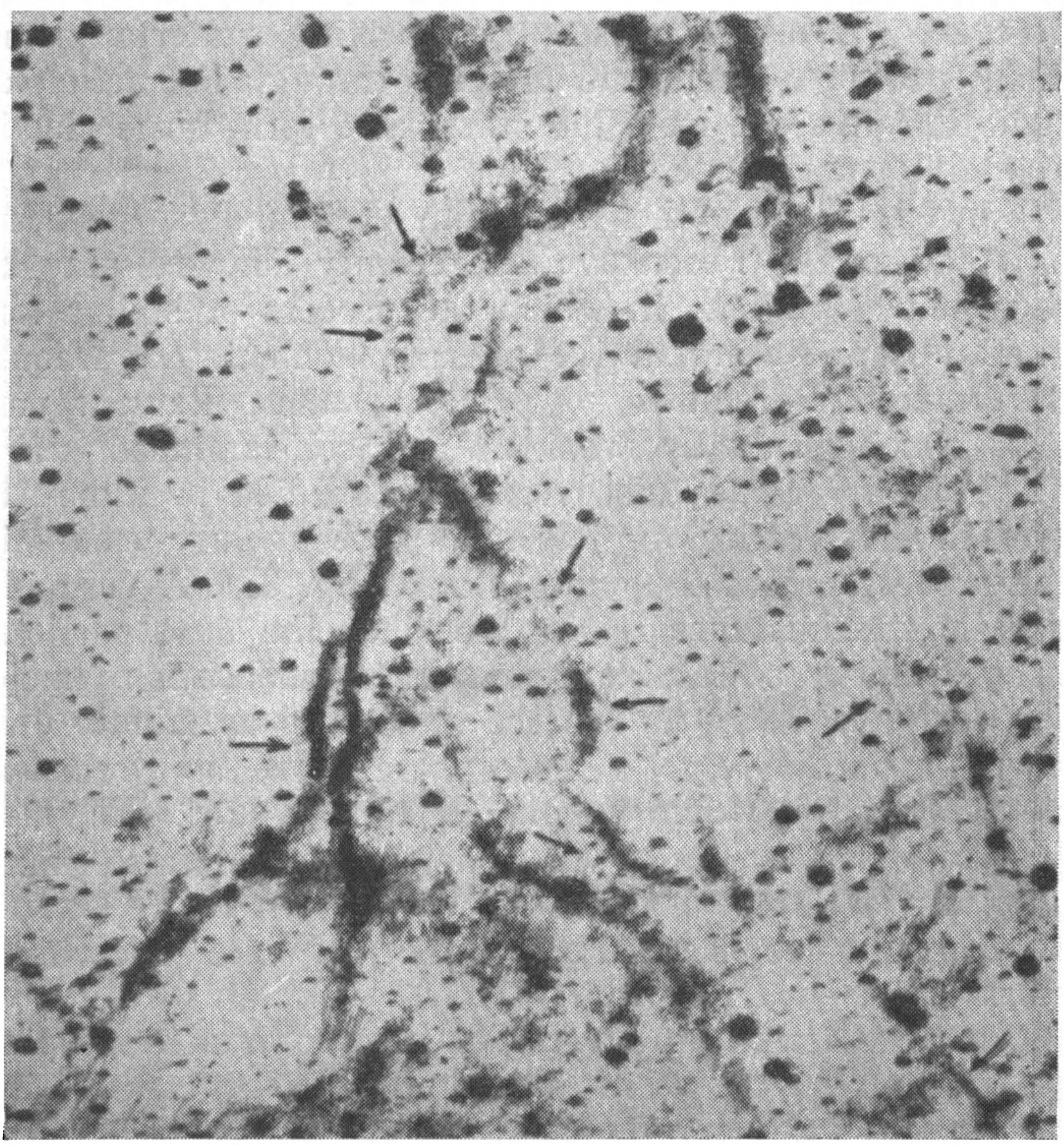


Fig. 32. Filaments and condensations (denoted by arrows) in the gaseous-dust nebula in the constellation of Cygnus

ment of the Galaxy. We have already pointed out that minute dust particles and molecules of gas are constantly being ejected from the solar system during the disintegration of comets and meteors. The very same mechanism should also be operative in the many millions of planetary systems of other stars. This means that the interstellar dust medium is constantly being replenished by products that arise in the development of stars and planetary systems. The concentration of stars near the plane of the Galaxy is related to the fact that the dark dust nebulae, which are constantly receiving material from disintegrating comets and meteors through the action of radiation pressure from the stars, also form large clouds near this same plane.

Viewed from another side, the gaseous-dust nebulae, as Academician Fesenkov has recently shown, may be regarded as regions in which the process of stellar formation is operating at the present moment. A gaseous-dust medium produces powerful turbulent filament vortices which gradually break up into self-luminous stars. The "stellar chains" discovered and studied in Alma-Ata are filament vortices or jets of a gaseous-dust nebula in the process of break-up into stars (Fig. 32). A very important circumstance is the fact that the dust particles in gaseous-dust nebulae represent condensation nuclei for gas molecules in much the same way as minute dust particles in the earth's atmosphere serve as condensation nuclei for water vapour in rain clouds. We may guess that the origin of the cometary cloud is also linked up with the condensation of matter in the remnants of filament vortices that break up into individual stars.

We thus arrive at a cycle of matter in a developing stellar universe in which interstellar dust plays an important part. Apparently, the situation in the stellar universe is like that in the solar system in that there are two simultaneously operating and opposite processes: one

of condensation and the other of disintegration and dispersion of matter.

There are no reasons to expect to encounter, in gaseous-dust nebulae, big bodies of complex structure like large-size meteorites. Rather may we expect to find dust particles of the size of microns, of simpler structure than the meteoric bodies of the solar system, that have covered a long path of development. For this reason, we cannot accept the original version of Academician Schmidt's cosmogonic hypothesis which suggests as building material for the planetary system a "cloud of meteorites" captured by the sun, all the more so since the capture process is a highly improbable thing from the mechanics point of view. The problem of the nature of interstellar dust matter and its relation to the meteoric matter of the solar system still awaits a definitive solution.

Dust matter is found not only in our Galaxy but far beyond its confines in other stellar systems. Photographs of the spiral stellar system of the Andromeda galaxy and many other remote stellar systems show clouds and filaments of dark dust. These masses of dust are especially evident in spiral galaxies viewed edge on. Dust matter is an abundant component of the entire visible universe.

CONCLUSION

During the 150 years of its existence and development, meteor astronomy has amassed extensive material on the nature of meteors, their role in the solar system, and it has established the great significance that meteors have in studies of the upper layers of the earth's atmosphere.

There are still many unsolved problems that confront meteor astronomy and meteor geophysics in the study of the structure of the upper atmosphere by meteor methods. For instance, problems concerning time variations of the physical properties of the atmosphere and also their de-

pendence on the geographic position have hardly been touched on. Studies of circulation in the upper layers of the atmosphere have only begun. Again in the infant stage but now rapidly progressing is a series of studies dealing with the flight of rocket ships and artificial satellites in the upper atmosphere and in cosmic space.

There are still many unsolved problems related to the nature of meteors, their interrelationships with the other bodies of the solar system and their origin, which means that there are many years of intensive research work ahead of us in the study of meteors. This is a wide open field for those interested in meteor astronomy.

In this connection it should be stressed that amateur visual and photographic observations of meteors still retain their value. Any astronomy fan interested in the science of the sky and wishing to further its successes can take part in these observations that are conducted according to specially worked out programmes.

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